

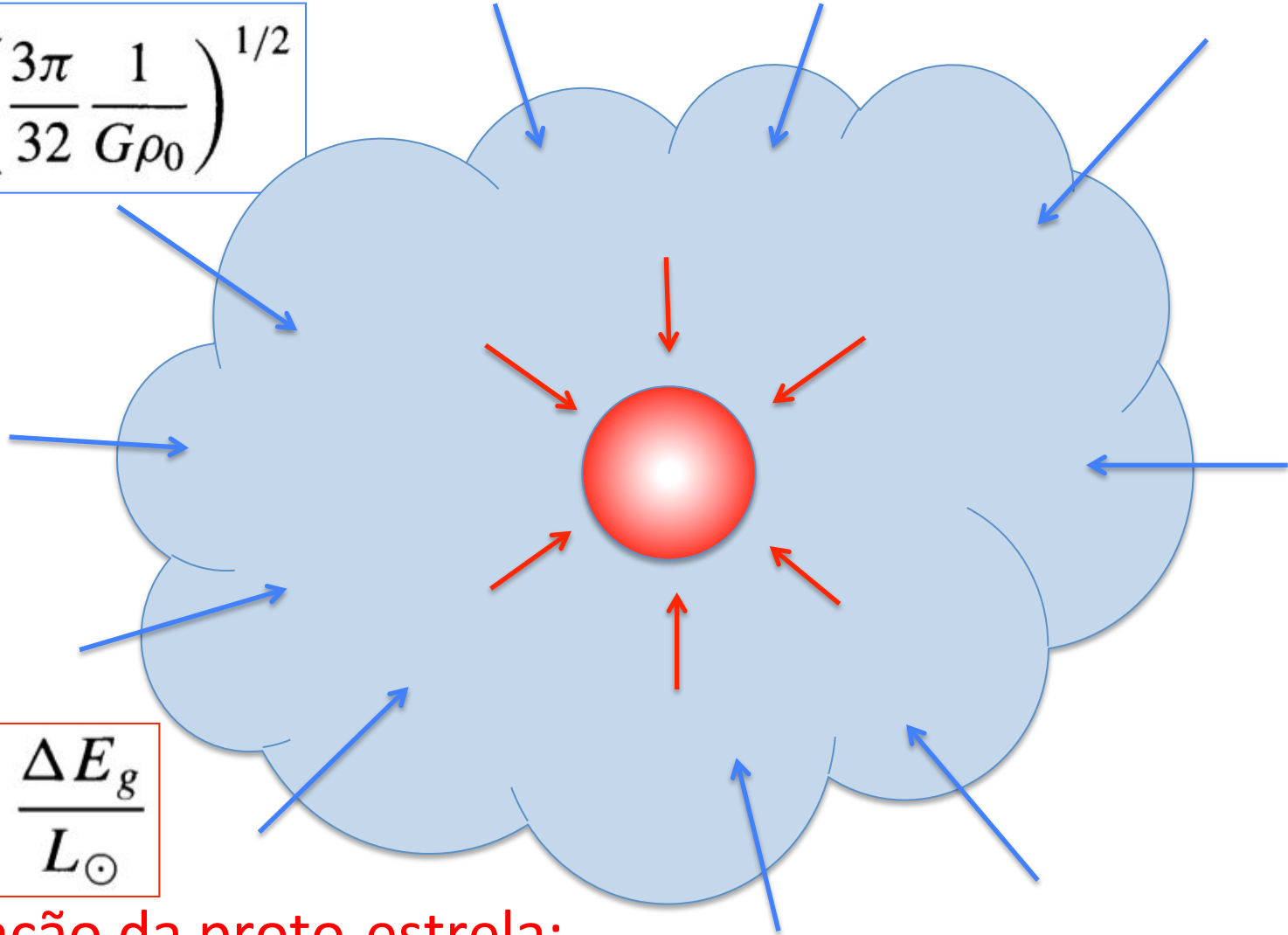
12 - O Meio Interestelar (ISM) e a Formação de Estrelas

12.3 Evolução pre-sequência principal + parte do 12.2 (colapso da nuvem a proto-estrela)

Jorge Meléndez

Colapso da nuvem: escala de tempo *free-fall* $\sim 10^5$ anos

$$t_{\text{ff}} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2}$$



$$t_{\text{KH}} = \frac{\Delta E_g}{L_{\odot}}$$

Contração da proto-estrela:
escala de tempo de Kelvin-Helmholtz $\sim 10^7$ de anos

Colapso homólogo

Escala de tempo de *free fall* para o colapso da nuvem:

$$t_{\text{ff}} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2}$$

O tempo de *free fall* não depende do raio da nuvem → colapso homólogo (todas as partes da nuvem colapsam no mesmo tempo)

Exemplo 12.2.2

Usando os dados do Exemplo 12.2.1, estimar o tempo de colapso da nuvem para uma proto-estrela.

$$\rho_0 = 3 \times 10^{-17} \text{kgm}^{-3} \rightarrow t_{\text{ff}} = 3,8 \times 10^5 \text{ anos}$$

Exemplo 10.3.1. Quanta energia teria liberado o Sol pelo colapso de proto-estrela a partir de um raio inicial muito maior ao atual?

$$E \sim -\frac{3}{10} \frac{GM^2}{R} \quad (\text{metade da energia potencial pode ser radiada})$$

Assumindo que uma proto-estrela tem $R_i \gg R_{\text{sol}}$:

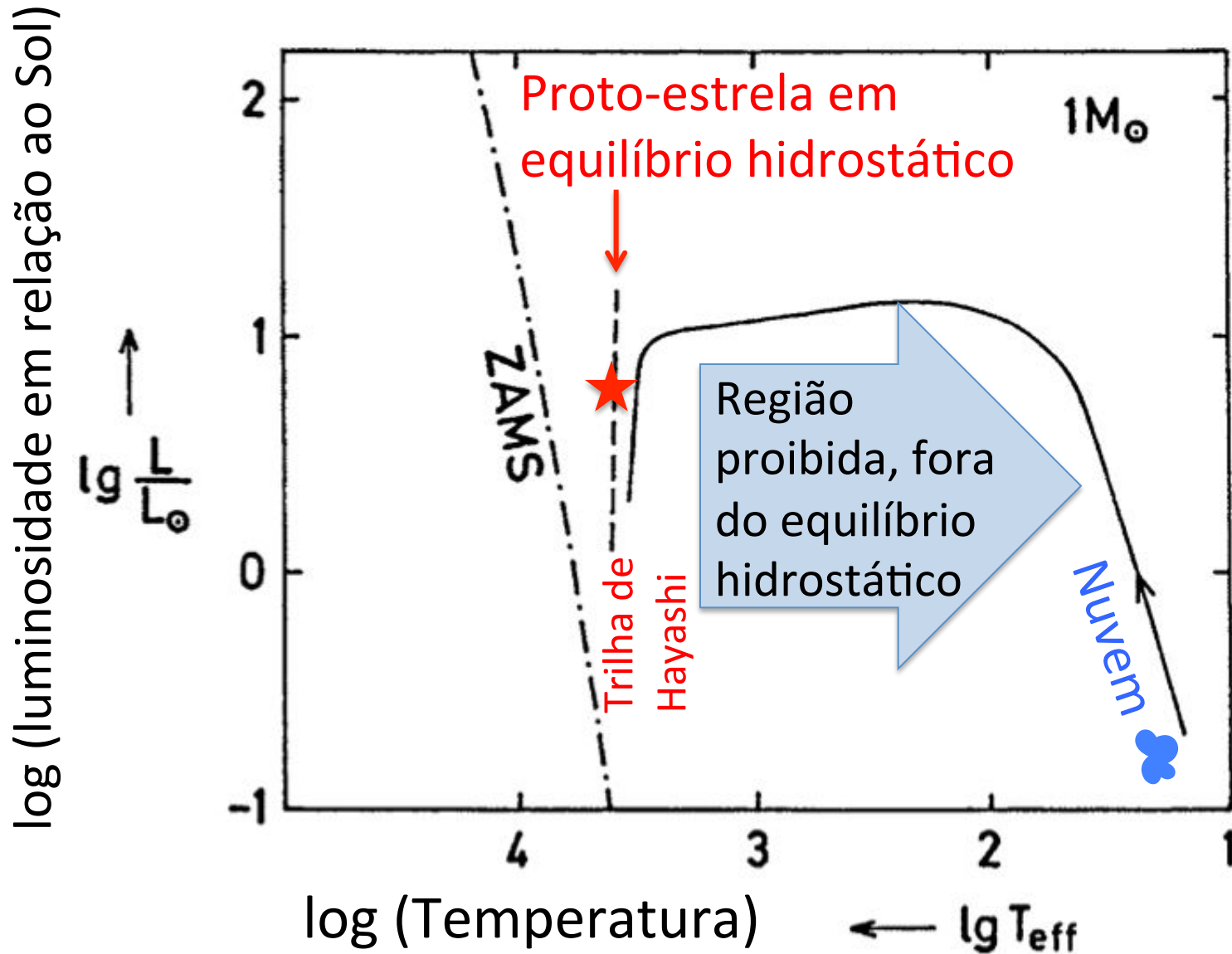
$$\Delta E_g = -(E_f - E_i) \simeq -E_f \simeq \frac{3}{10} \frac{GM_{\odot}^2}{R_{\odot}} \simeq 1.1 \times 10^{41} \text{ J.}$$

Supondo luminosidade aprox. constante para o Sol:

$$t_{\text{KH}} = \frac{\Delta E_g}{L_{\odot}} \sim 10^7 \text{ anos} \quad t_{\text{KH}} \text{ é a escala de tempo Kelvin-Helmholtz}$$

$t_{\text{KH}} \gg t_{\text{ff}} \rightarrow$ a evolução da proto-estrela acontece lentamente (comparada ao colapso da nuvem)

Colapso de nuvem ☁ a proto-estrela ★



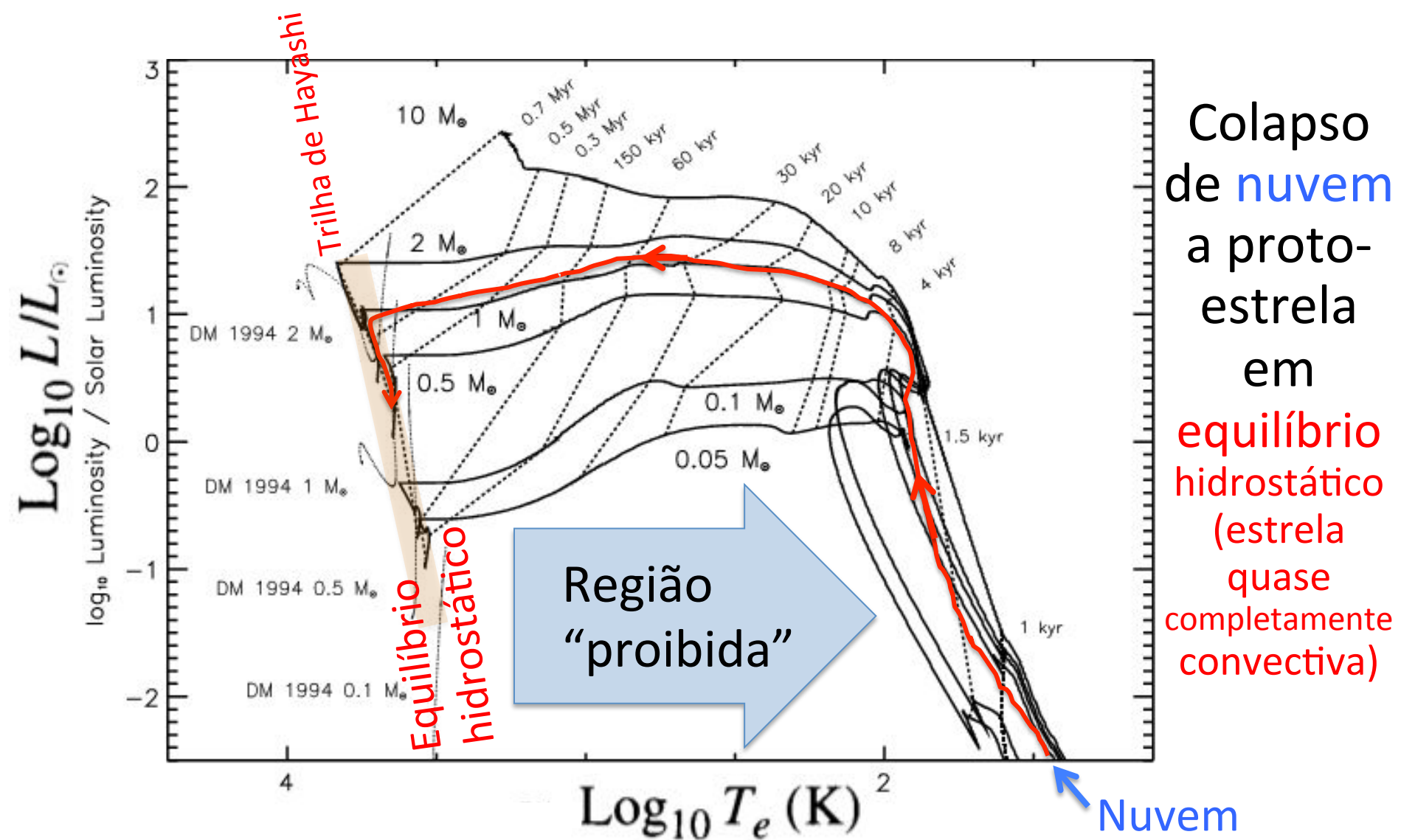
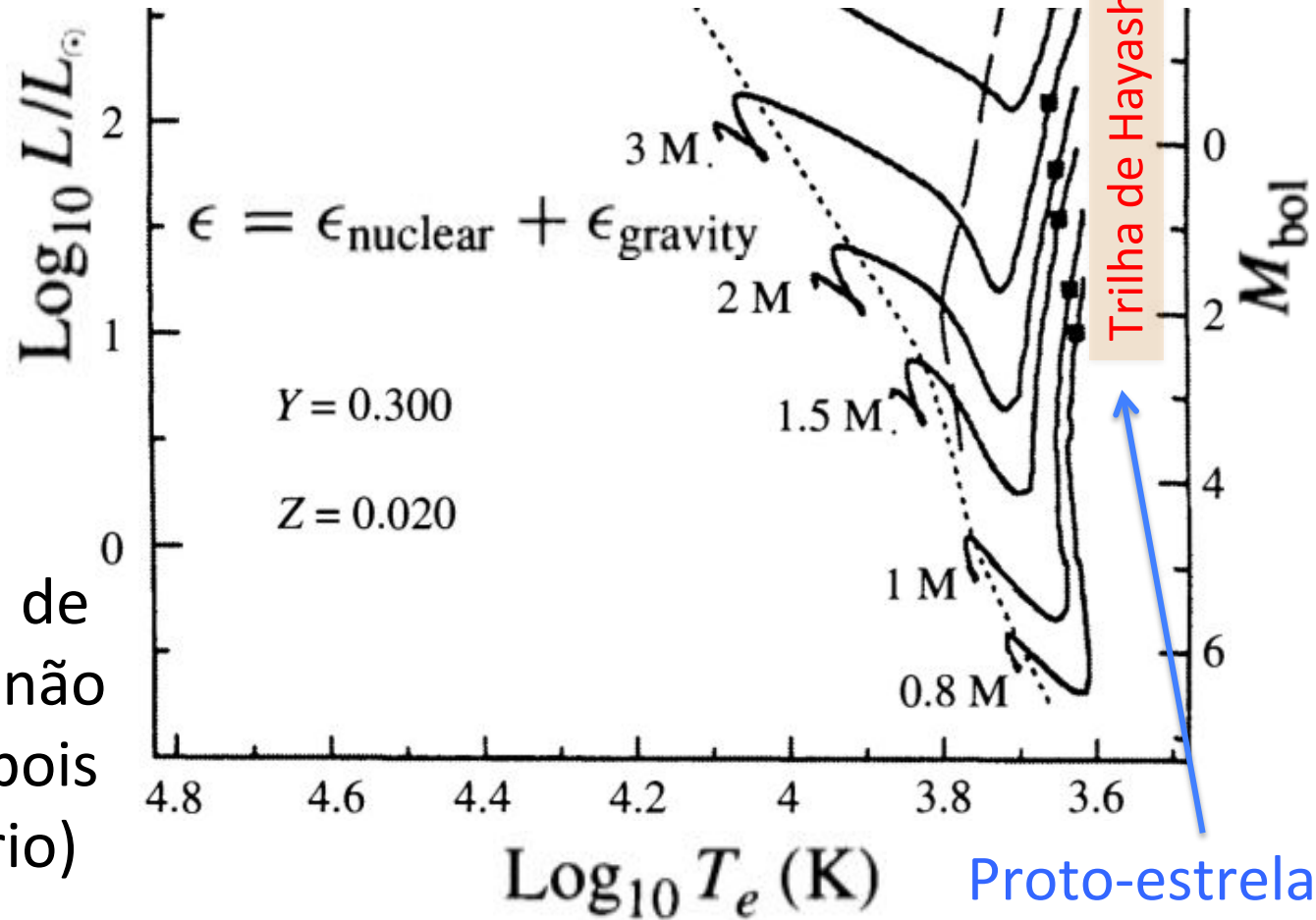


FIGURE 12.9 Theoretical evolutionary tracks of the gravitational collapse of 0.05, 0.1, 0.5, 1, 2, and 10 $M_{\odot}$ clouds through the protostar phase (solid lines). The dashed lines show the times since collapse began. The light dotted lines are pre-main-sequence evolutionary tracks of 0.1, 0.5, 1, and 2 $M_{\odot}$ stars from D'Antona and Mazzitelli, *Ap. J. Suppl.*, 90, 457, 1994. Note that the horizontal axis is plotted with effective temperature increasing to the left, as is characteristic of all H–R diagrams. (Figure adapted from Wuchterl and Tscharnuter, *Astron. Astrophys.*, 398, 1081, 2003.)

Cálculos clássicos de evolução na pré-Sequência Principal

■ Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)

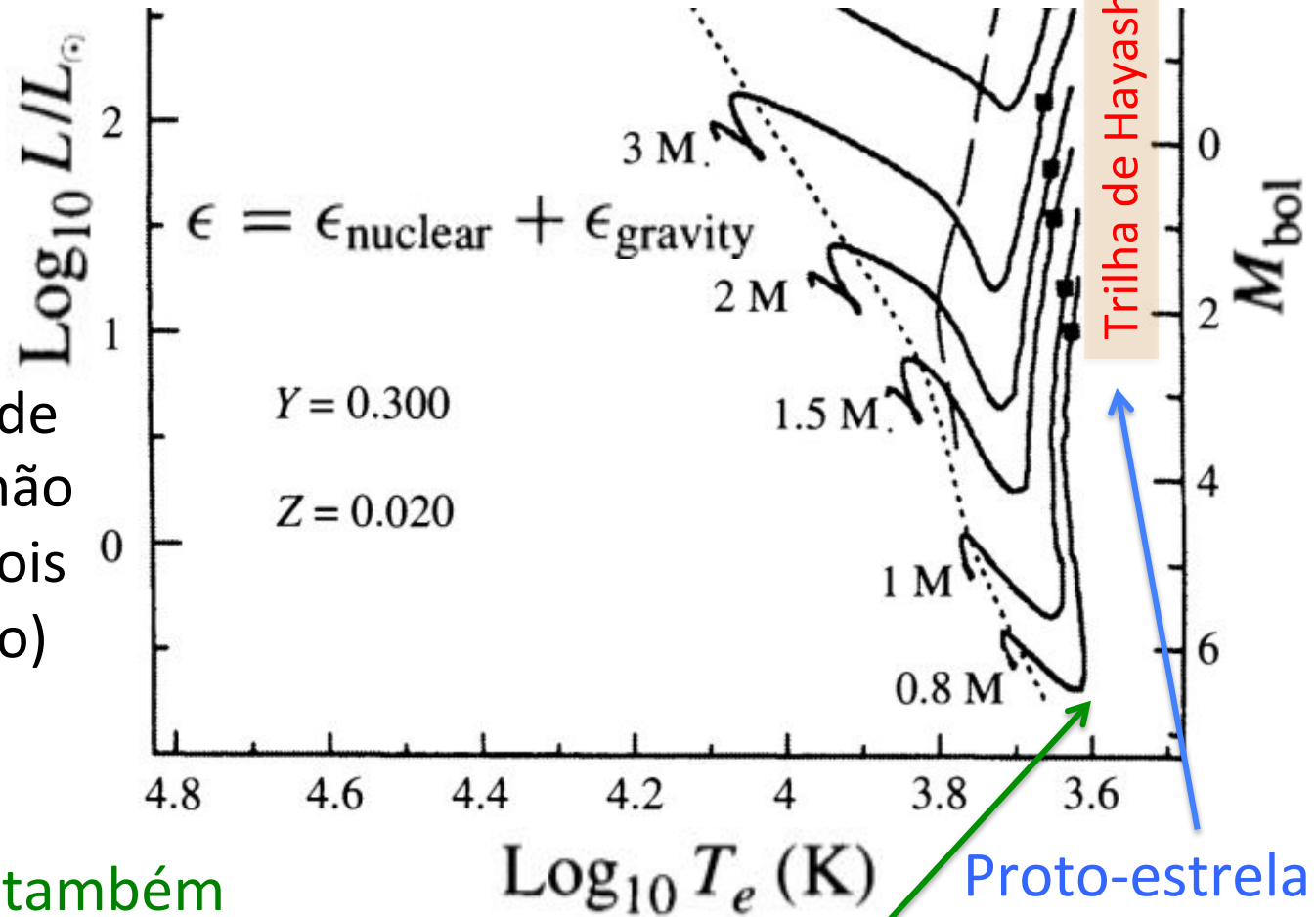


Proto-estrela completamente convectiva

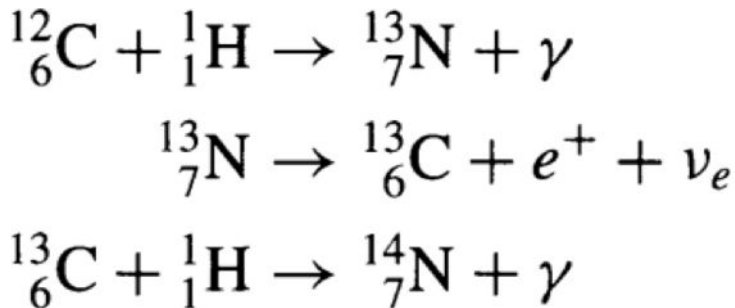
FIGURE 12.11 Classical pre-main-sequence evolutionary tracks computed for stars of various masses with the composition $X = 0.68$, $Y = 0.30$, and $Z = 0.02$. The direction of evolution on each track is generally from low effective temperature to high effective temperature (right to left). The mass of each model is indicated beside its evolutionary track. The square on each track indicates the onset of deuterium burning in these calculations. The long-dash line represents the point on each track where convection in the envelope stops and the envelope becomes purely radiative. The short-dash line marks the onset of convection in the core of the star. Contraction times for each track are given in Table 12.1. (Figure adapted from Bernasconi and Maeder, *Astron. Astrophys.*, 307, 829, 1996.)

Cálculos clássicos de evolução na pré-Sequência Principal

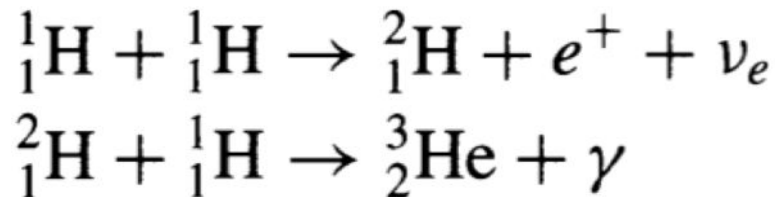
- ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$
Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)



Para $M > 0,5 M_{\text{sol}}$ também temos ${}^{12}\text{C} \rightarrow {}^{14}\text{N}$



Núcleo radiativo.
Começa p-p



Cálculos clássicos de evolução na pré-Sequência Principal

■ $^2_1\text{H} + ^1_1\text{H} \rightarrow ^3_2\text{He} + \gamma$
 Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)

— — Fim da convecção no envelope → envelope radiativo

----- Começo da convecção no núcleo da estrela

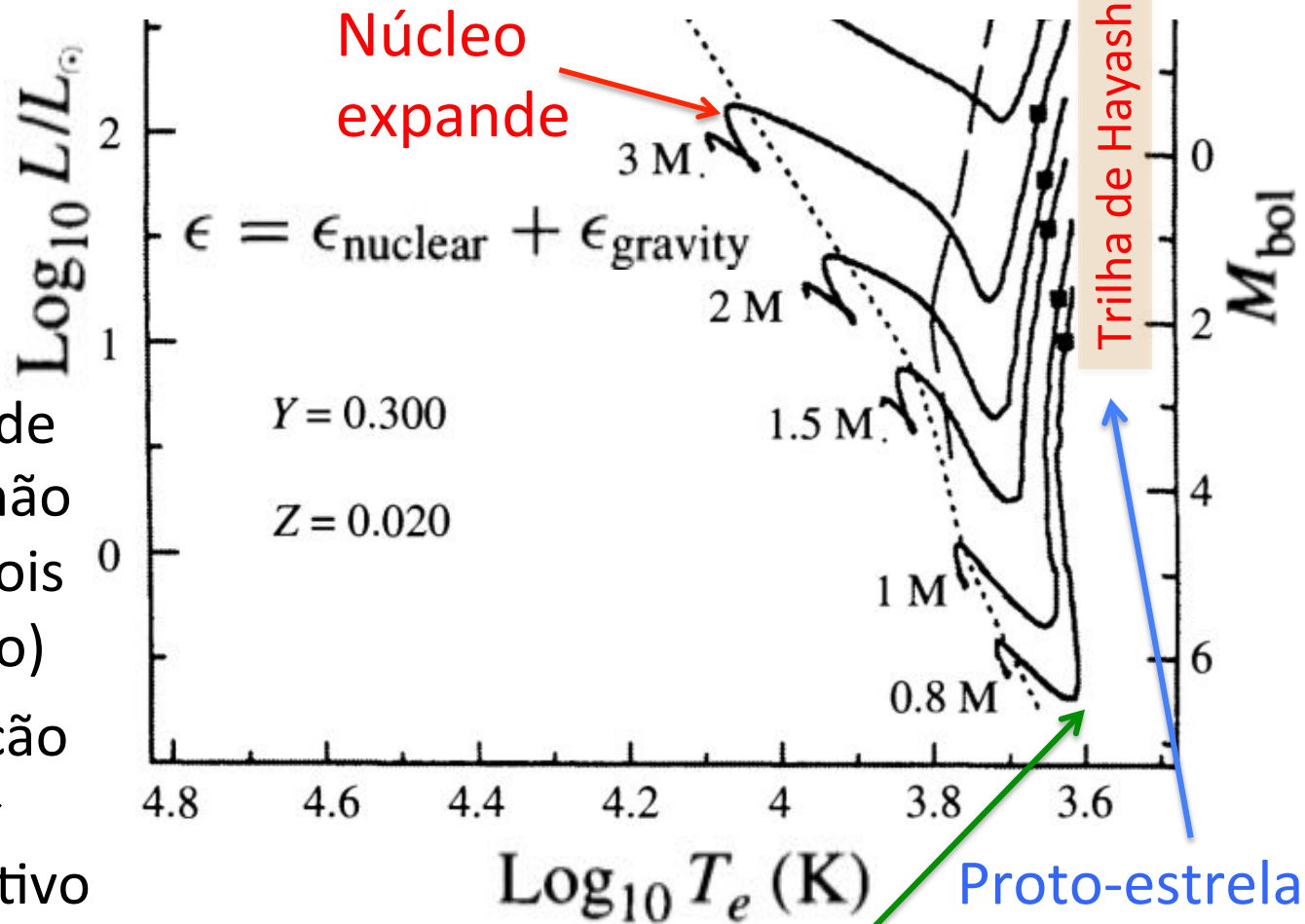
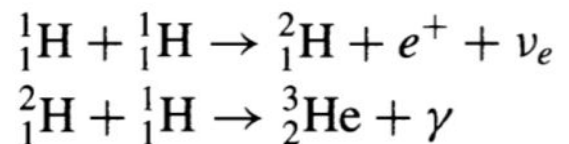


FIGURE 12.11 Classical pre-main-sequence evolutionary tracks computed for stars of various masses with the composition $X = 0.68$, $Y = 0.30$, and $Z = 0.02$. The direction of evolution on each track is generally from low effective temperature to high effective temperature (right to left). The mass of each model is indicated beside its evolutionary track. The square on each track indicates the onset of deuterium burning in these calculations. The long-dash line represents the point on each track where convection in the envelope stops and the envelope becomes purely radiative. The short-dash line marks the onset of convection in the core of the star. Contraction times for each track are given in Table 12.1. (Figure adapted from Bernasconi and Maeder, *Astron. Astrophys.*, 307, 829, 1996.)

Núcleo radiativo.

Começa p-p



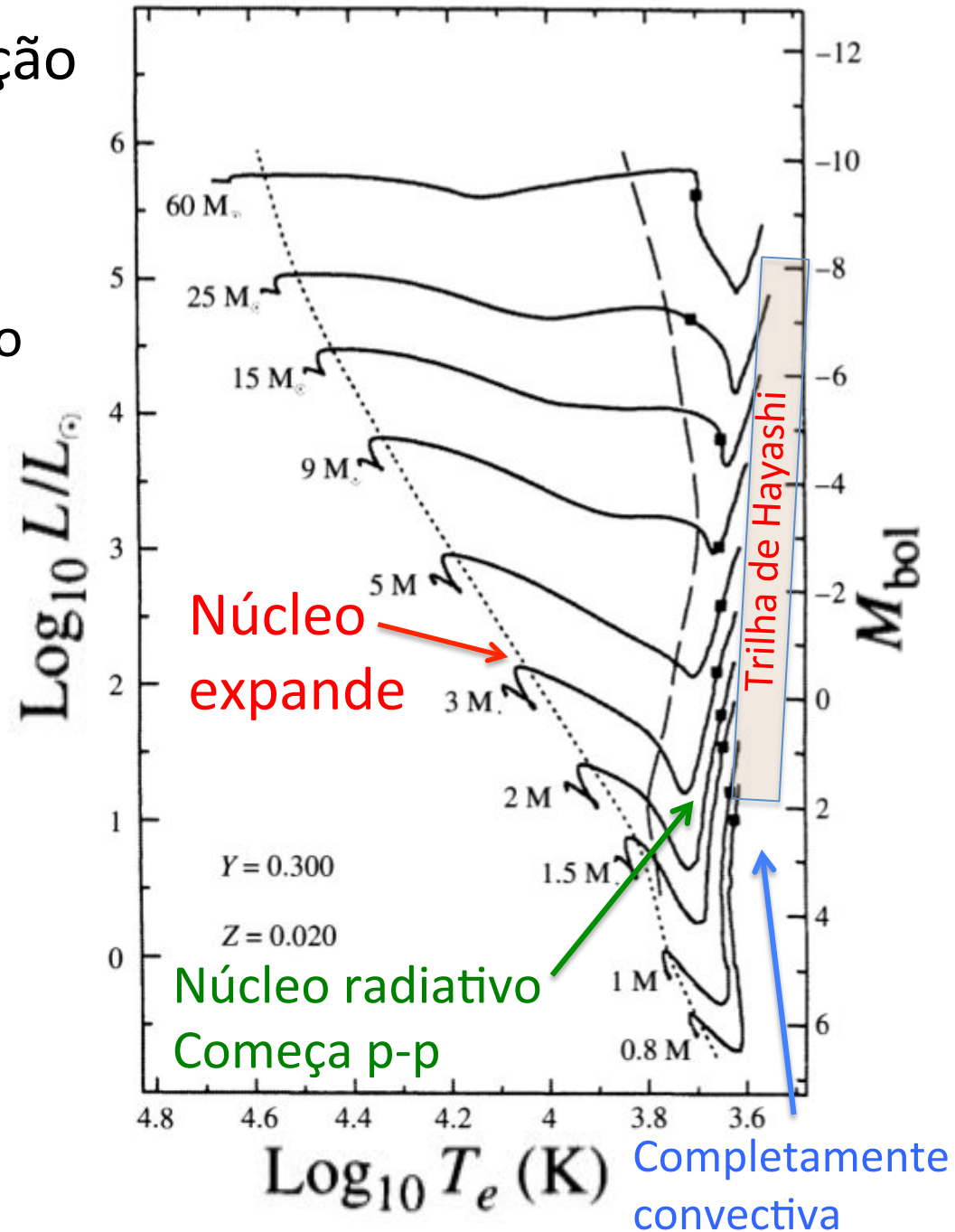
Cálculos clássicos de evolução na pré-Sequência Principal (contração da proto-estrela)

■ Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)

--- Fim da convecção no envelope → envelope puramente radiativo

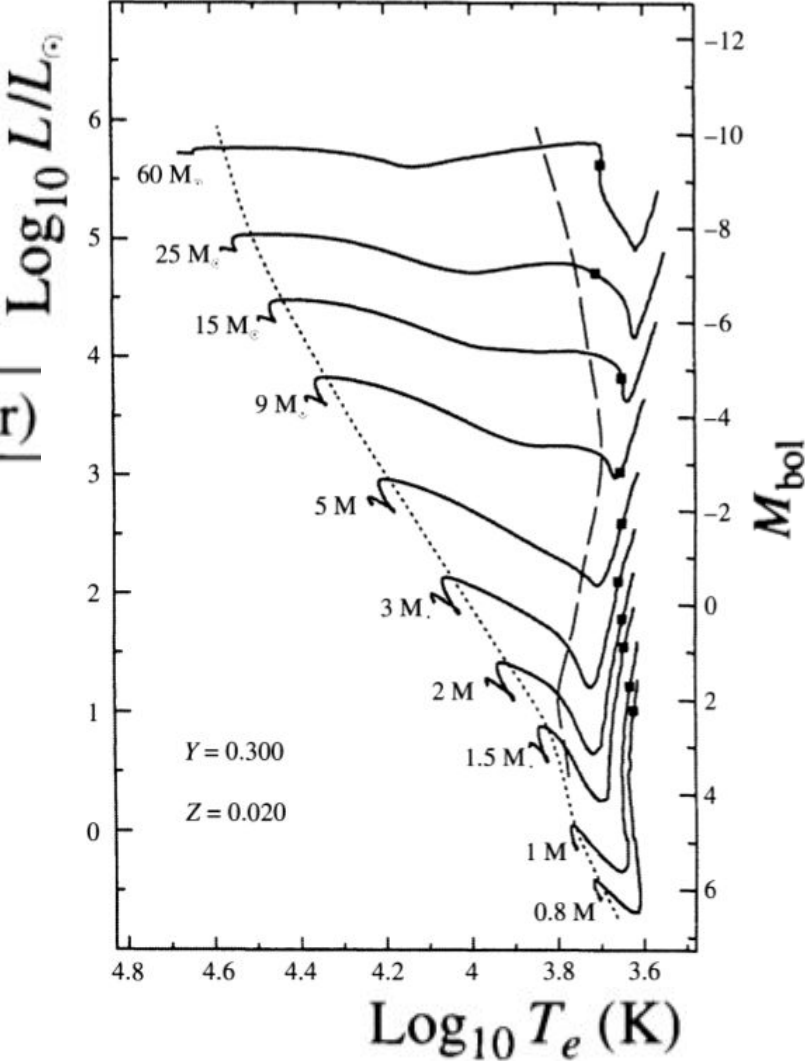
--- Começo da convecção no núcleo da estrela

$$\epsilon = \epsilon_{\text{nuclear}} + \epsilon_{\text{gravity}}$$



Cálculos clássicos de evolução na pré-Sequência Principal (contração da proto-estrela)

Initial Mass ($M_{\odot}$)	Contraction Time (Myr)
60	0.0282
25	0.0708
15	0.117
9	0.288
5	1.15
3	7.24
2	23.4
1.5	35.4
1	38.9
0.8	68.4



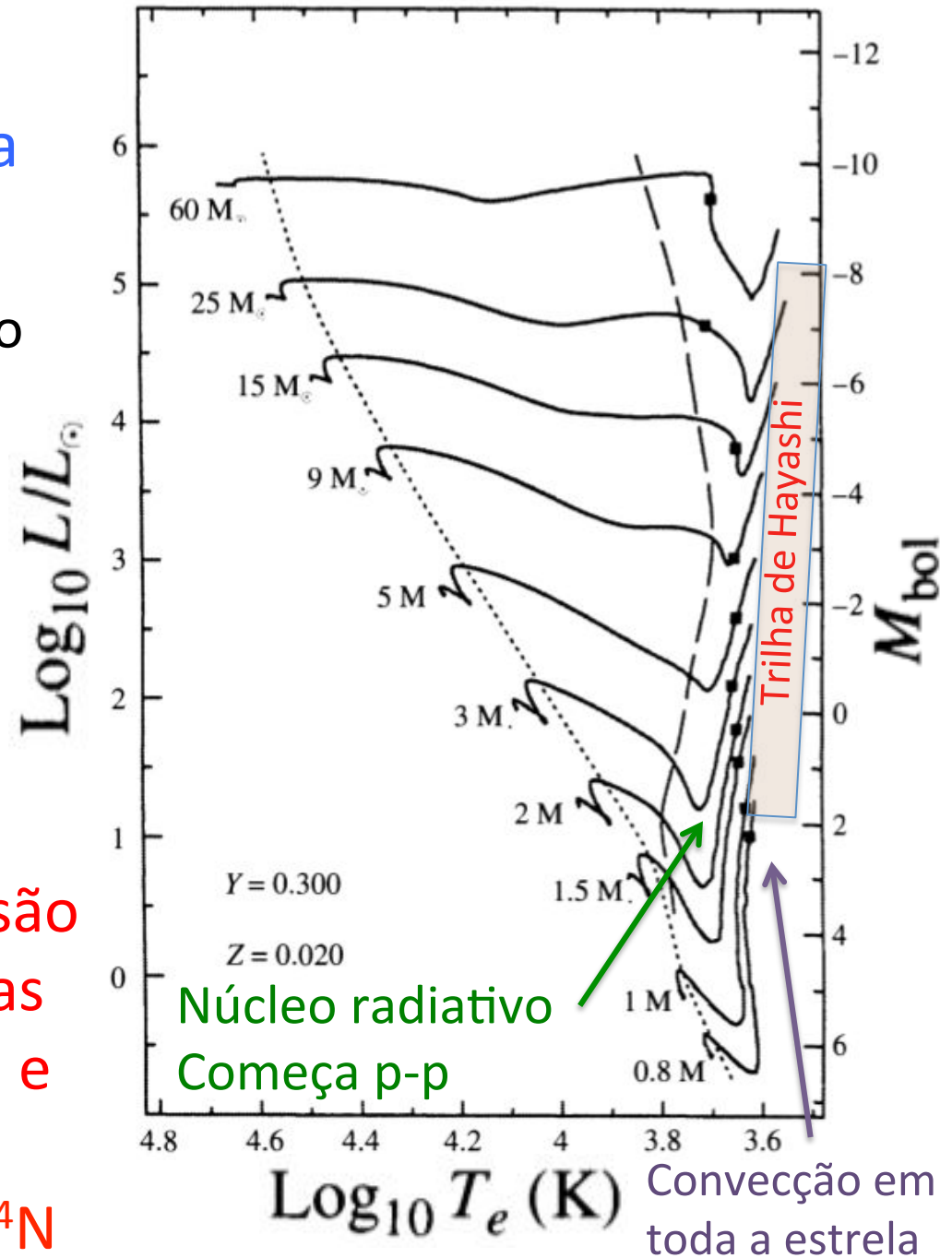
Estrelas massivas: núcleo convectivo mesmo após a pré-Sequência principal

■ Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)

--- Fim da convecção no envelope → envelope puramente radiativo

--- Começo da convecção no núcleo da estrela

Estrelas com $M < 0,5 M_{\text{Sol}}$ são completamente convectivas na pré-Sequência Principal e na Sequência Principal. Elas não queimam $^{12}\text{C} \rightarrow ^{14}\text{N}$

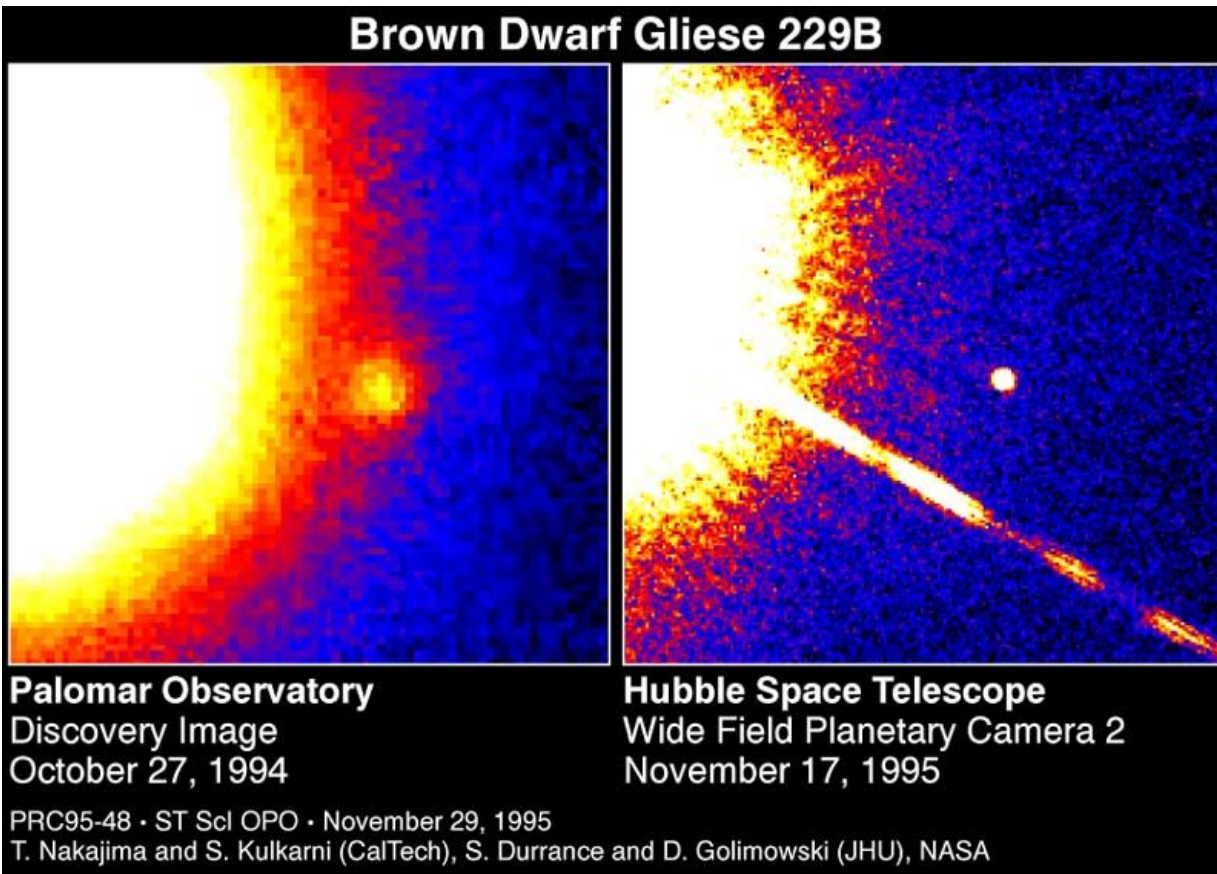


Se M da proto-estrela $< 0,072 M_{\text{Sol}}$ $\rightarrow$ temperatura baixa demais para a queima de H

$M > 0,06 M_{\text{Sol}}$ $\rightarrow$ queima de Li

$M > 0,013 M_{\text{Sol}}$ $\rightarrow$ queima de deutério

Anãs marrons: $0,013 < M/M_{\text{Sol}} < 0,072$

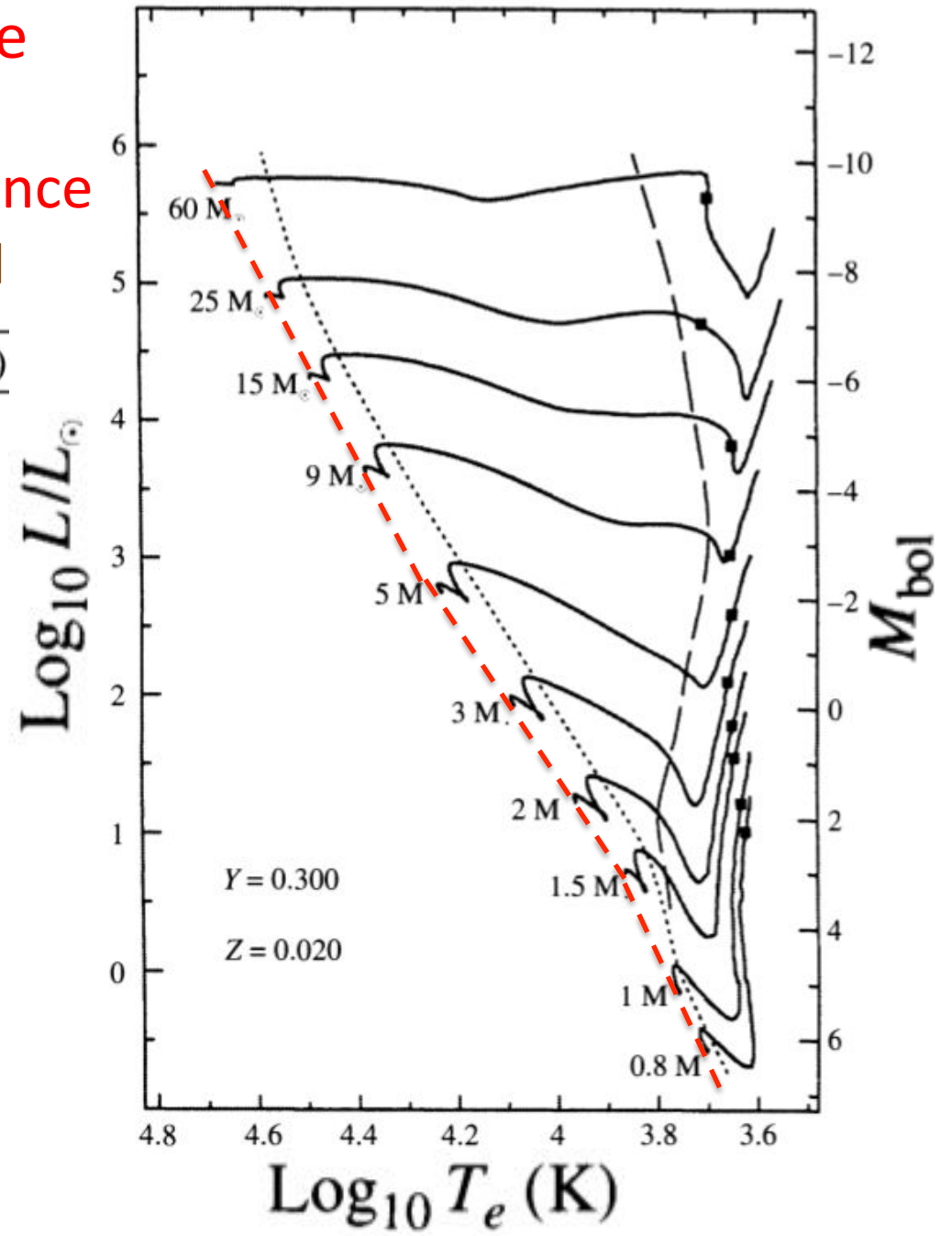


Tipos espectrais
L e T

----- Sequência Principal de Idade Zero

ZAMS: Zero-Age Main Sequence
Começa queima estável de H

Initial Mass ($M_{\odot}$)	Contraction Time (Myr)
60	0.0282
25	0.0708
15	0.117
Estrelas massivas se formam muito mais rapidamente do que estrelas de baixa massa	
9	0.288
5	1.15
3	7.24
2	23.4
1.5	35.4
1	38.9
0.8	68.4



Near the outskirts of the Small Magellanic Cloud, lies the young star cluster NGC 602, surrounded by natal gas and dust. Fantastic ridges and undulating shapes strongly suggest that energetic radiation and shock waves from NGC 602's massive young stars have eroded the dusty material and triggered a progression of star formation moving away from the cluster's center.



A Função de Massa Inicial (IMF)

Initial Mass Function

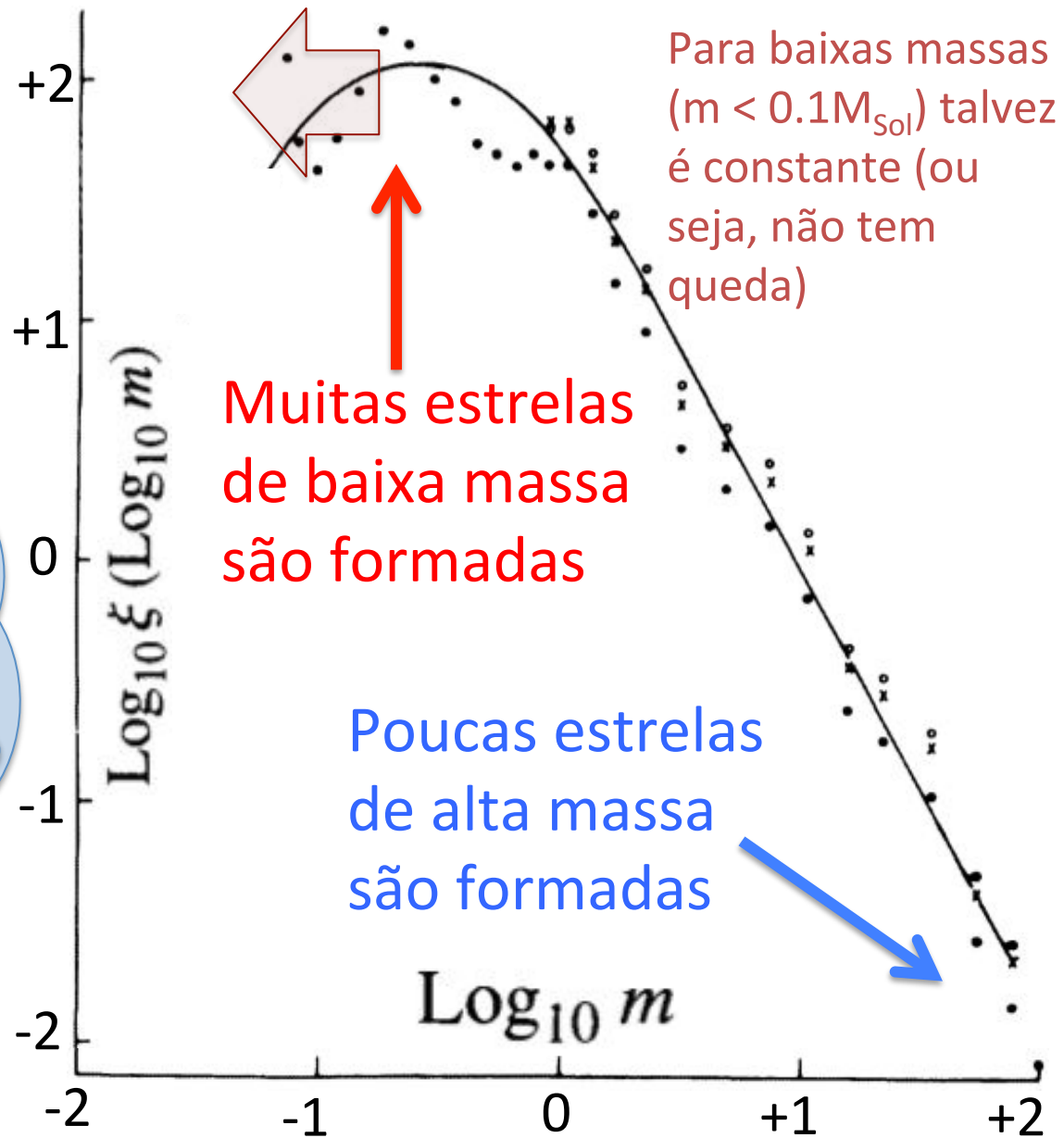
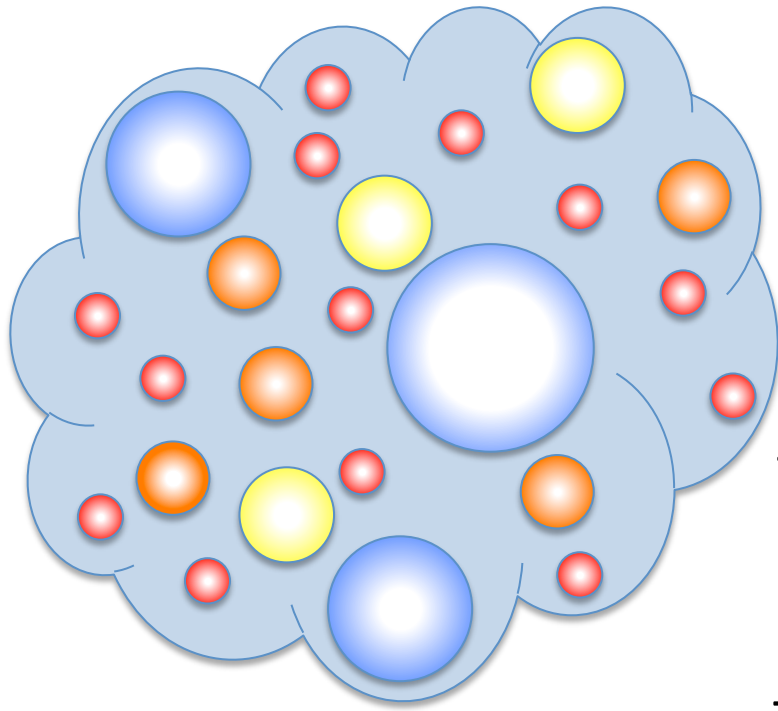
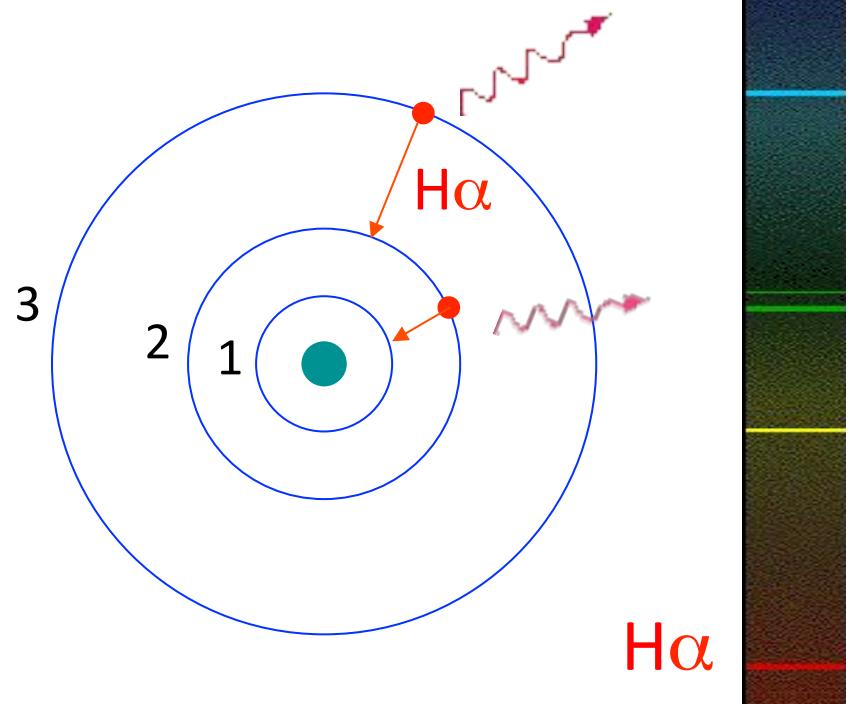


FIGURE 12.12 The initial mass function, ξ , shows the number of stars per unit area of the Milky Way's disk per unit interval of logarithmic mass that is produced in different mass intervals. The individual points represent observational data and the solid line is a theoretical estimate. Masses are in solar units. (Figure adapted from Rana, *Astron. Astrophys.*, 184, 104, 1987.)

Regiões H II

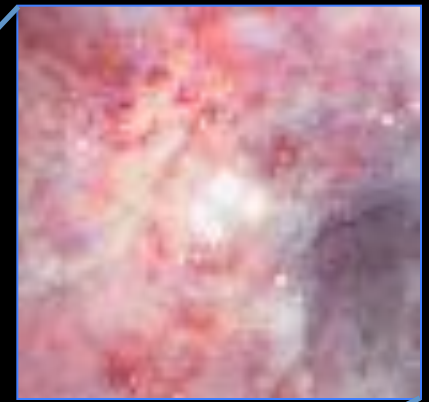
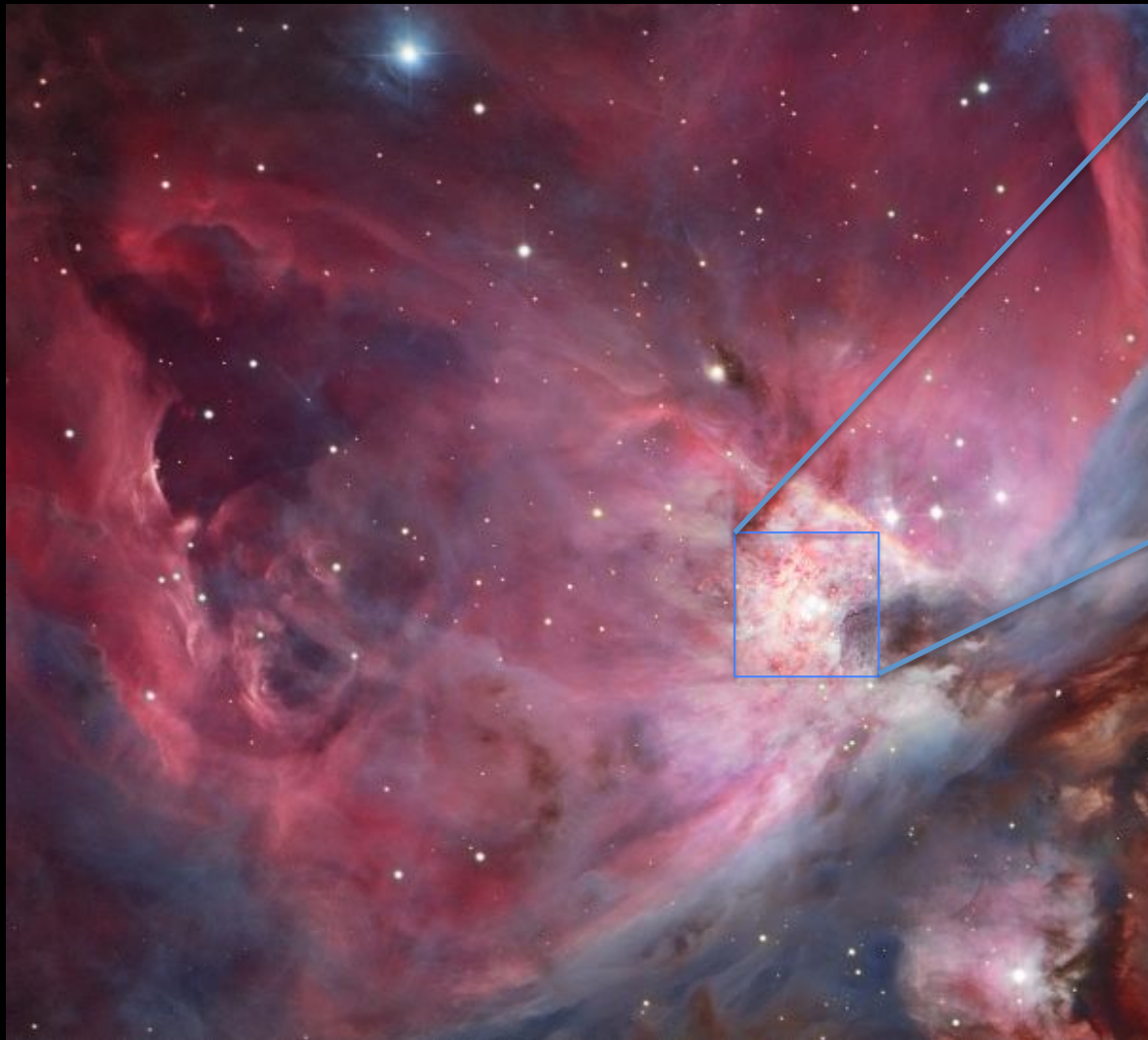
- Temperatura ~ 8000 K
- Luz UV de estrelas O e B pode ionizar nuvens de gás de hidrogênio neutro ($E > 13,6$ eV para ionizar H do estado base)
- Elétrons recombinaem e decaem a estados menos excitados. No visível, a radiação dominante é devida à transição $n=3 \rightarrow 2$, o que dá a cor vermelha (**$H\alpha$: 656,3 nm**)



Nebulosa de Orion: região H II



Trapezium cluster @ Orion Nebula



Hubble, infrared



Tamanho de Regiões H II

$\alpha n_e n_H$: número de recombinações por unidade de V por segundo

α : coeficiente de recombinação (probabilidade de $e + p \rightarrow H$)

Para cada íon de H, um e^- é liberado: $n_e = n_H$

Em equilíbrio, o número total de fótons ionizantes por segundo, N , deve ser igual ao número de recombinações por segundo:

$$\alpha n_H^2 V = N$$

Supondo
região HII
esférica:

$$V = \frac{4}{3}\pi r^3$$

Raio de Strömngren:

$$r_S \simeq \left(\frac{3N}{4\pi\alpha} \right)^{1/3} n_H^{-2/3}$$

N : número total de fótons ionizantes ($\lambda < 91,2 \text{ nm}$) por segundo

n_H : densidade numérica de H

α : coeficiente de recombinação. $\sim 3,1 \times 10^{-19} \text{ m}^3 \text{ s}^{-1}$ ($T = 8000 \text{ K}$)

Example 12.3.1. From Appendix G, the effective temperature and luminosity of an O6 star are $T_e \simeq 45,000$ K and $L \simeq 1.3 \times 10^5 L_\odot$, respectively. According to Wien's law (Eq. 3.15), the peak wavelength of the blackbody spectrum is given by

$$\lambda_{\max} = \frac{0.0029 \text{ m K}}{T_e} = 64 \text{ nm}$$

Since this is significantly shorter than the 91.2-nm limit necessary to produce ionization from the hydrogen ground state, it can be assumed that most of the photons created by an O6 star are capable of causing ionization.

The energy of one 64-nm photon can be calculated from Eq. (5.3), giving

$$E_\gamma = \frac{hc}{\lambda} = 19 \text{ eV}$$

Now, assuming for simplicity that all of the emitted photons have the same (peak) wavelength, the total number of photons produced by the star per second is just

$$N \simeq L/E_\gamma \simeq 1.6 \times 10^{49} \text{ photons s}^{-1}$$

taking $n_H \sim 10^8 \text{ m}^{-3}$ to be a typical value in an H II region, we find

$$r_S \simeq 3.5 \text{ pc} \quad r_S \simeq \left(\frac{3N}{4\pi\alpha} \right)^{1/3} n_H^{-2/3}$$

Values of r_S range from less than 0.1 pc to greater than 100 pc.

Imagem no infravermelho da Nebulosa Carina (@ESO)

- Estrelas massivas podem dispersar o resto da nuvem, dificultando a formação de estrelas
- Novos grupos de estrelas podem estar fracamente ligados gravitacionalmente devido à perda de massa da nuvem



FIGURE 12.15 The giant gas pillars of the Eagle Nebula (M16). The left most pillar is more than 1 pc long from base to top. Ionizing radiation from massive newborn stars off the top edge of the image are causing the gas in the cloud to photoevaporate. [Courtesy of NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University).]

Associações OB

- São grupos dominados por estrelas O e B
- De acordo a diferentes estudos essas estrelas estão no processo de ser dispersadas

Exemplo.

Aglomerado do Trapezio

- Idade < 10 milhões de anos
- Densamente populado
(densidade $\sim 2000 \text{ pc}^{-3}$)
- Medidas da velocidade do gás sugerem que o gás está sendo dispersado $\rightarrow$ *cluster unbound*



Trapezium cluster in the infrared
© Hubble

Estrelas T Tauri

- Estrelas de baixa massa ($0,5 - 2 M_{\text{sol}}$) da pré-Sequência Principal
- Variabilidade
- Alta rotação
- Muitas apresentam fortes linhas de emissão em $H\alpha$ e CaII
- Algumas linhas proibidas
→ gás em baixa densidade
- Forte absorção em Li

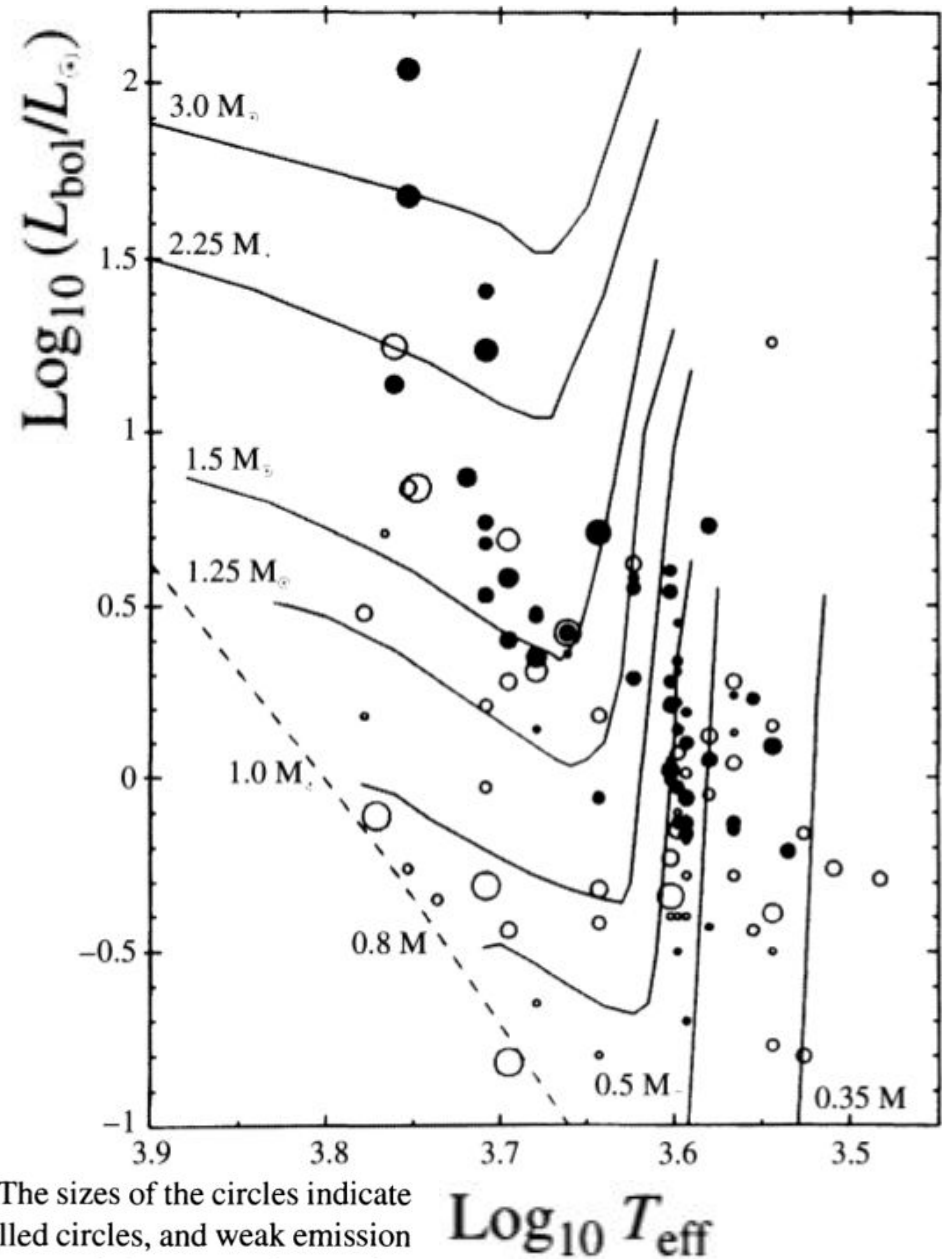


FIGURE 12.16 The positions of T Tauri stars on the H-R diagram. The sizes of the circles indicate the rate of rotation. Stars with strong emission lines are indicated by filled circles, and weak emission line stars are represented by open circles. Theoretical pre-main-sequence evolutionary tracks are also included. (Figure adapted from Bertout, *Annu. Rev. Astron. Astrophys.*, 27, 351, 1989. Reproduced with permission from the *Annual Review of Astronomy and Astrophysics*, Volume 27, ©1989 by Annual Reviews Inc.)

Estrelas T Tauri: perfis de linha P-Cygni

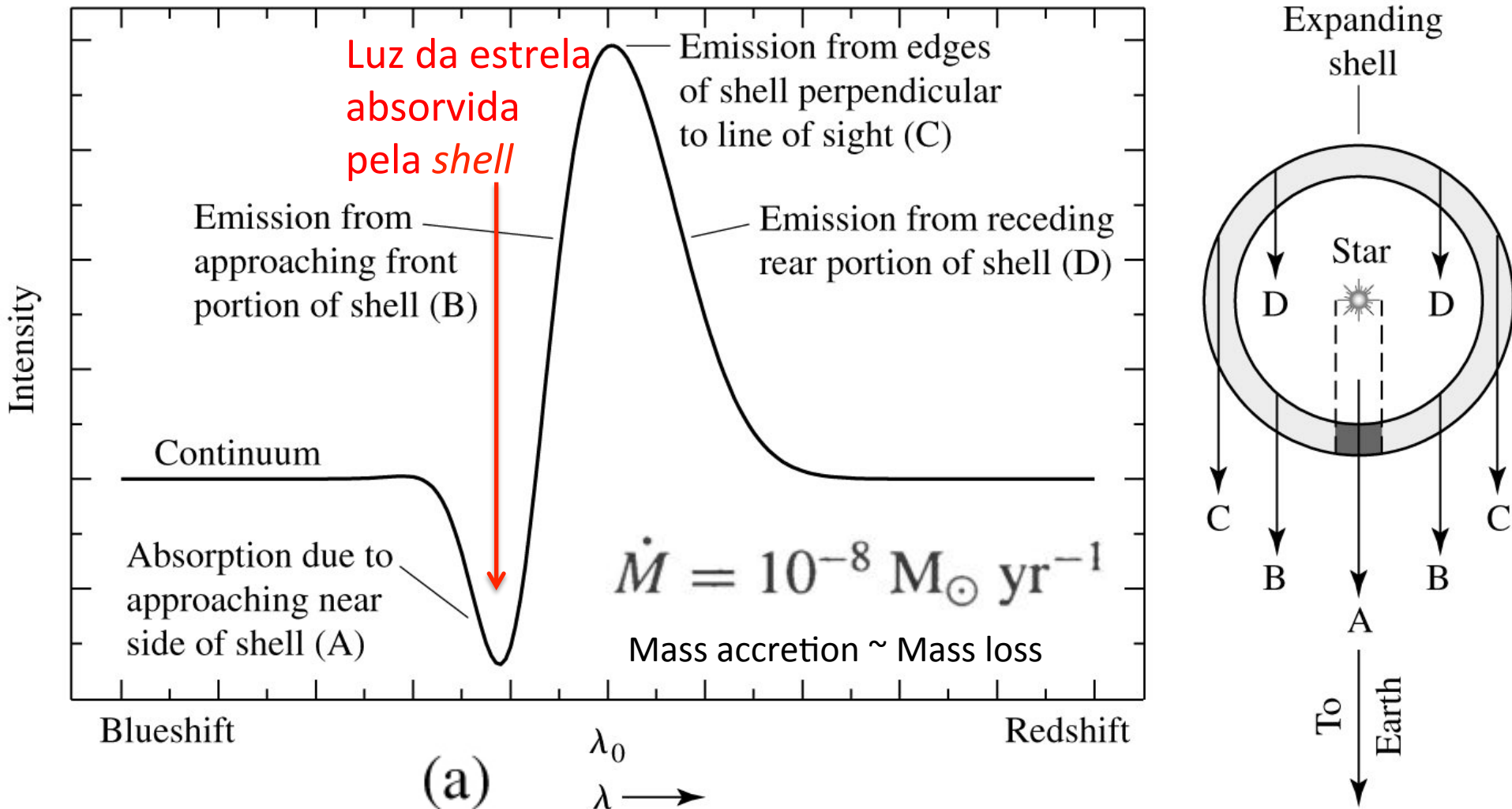


FIGURE 12.17 (a) A spectral line exhibiting a P Cygni profile is characterized by a broad emission peak with a superimposed blueshifted absorption trough. (b) A P Cygni profile is produced by an expanding mass shell. The emission peak is due to the outward movement of material perpendicular to the line of sight, whereas the blueshifted absorption feature is caused by the approaching matter in the shaded region, intercepting photons coming from the central star.

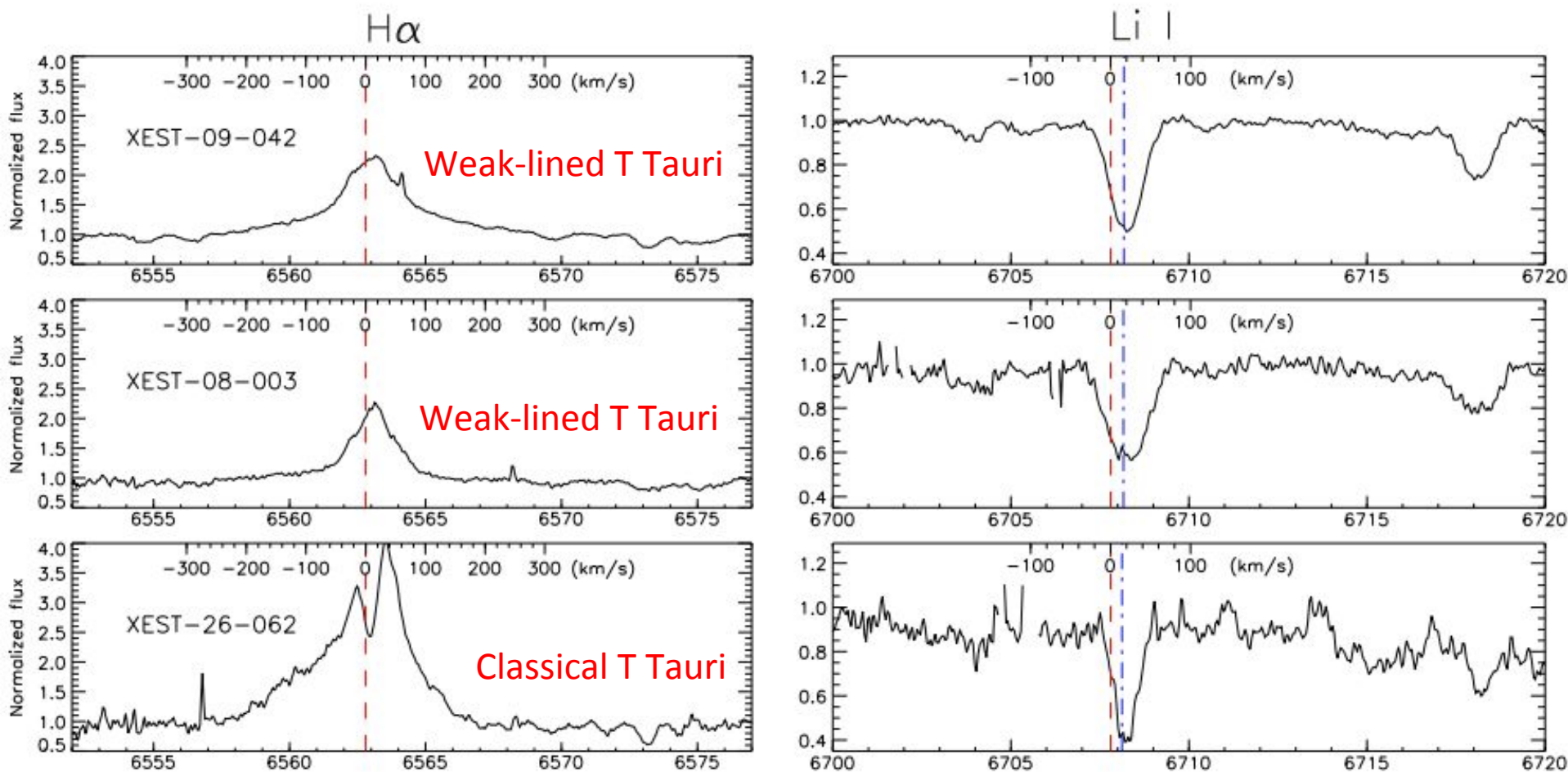


Fig. 2. High-resolution spectral regions (normalized to the continuum) centered around the H α (left panels) and Li I 6708 Å (right panels) lines. The red dashed vertical line in each plot marks the nominal wavelength of the spectral line; the blue dot-dashed lines in the right panels show the expected positions in the stellar spectrum of the Li line, based on the radial velocity shift. A velocity scale is reported on top of each panel. All prominent and narrow emission features in the plotted spectra (including that in the right side of the H α profile of XEST-09-042) are due to cosmic rays or hot pixels.

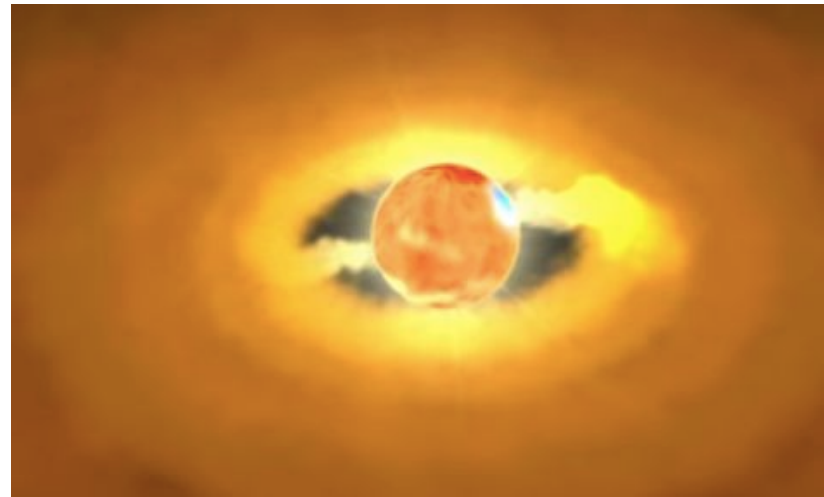
Estrelas FU Orionis

- Às vezes as estrelas T Tauri podem sofrer um aumento na acreção de massa

$$\dot{M} = 10^{-4} M_{\odot} \text{ yr}^{-1}$$

- Luminosidade incrementa em ~ 4 ordens de grandeza. Isso pode durar décadas.
- Essa instabilidade pode ser devida a uma grande acreção de massa ($\sim 0,01 M_{\text{sol}}$)
- Estrelas T Tauri podem passar por vários episódios FU Orionis

Imagem artística, NASA.
V1647 Orionis



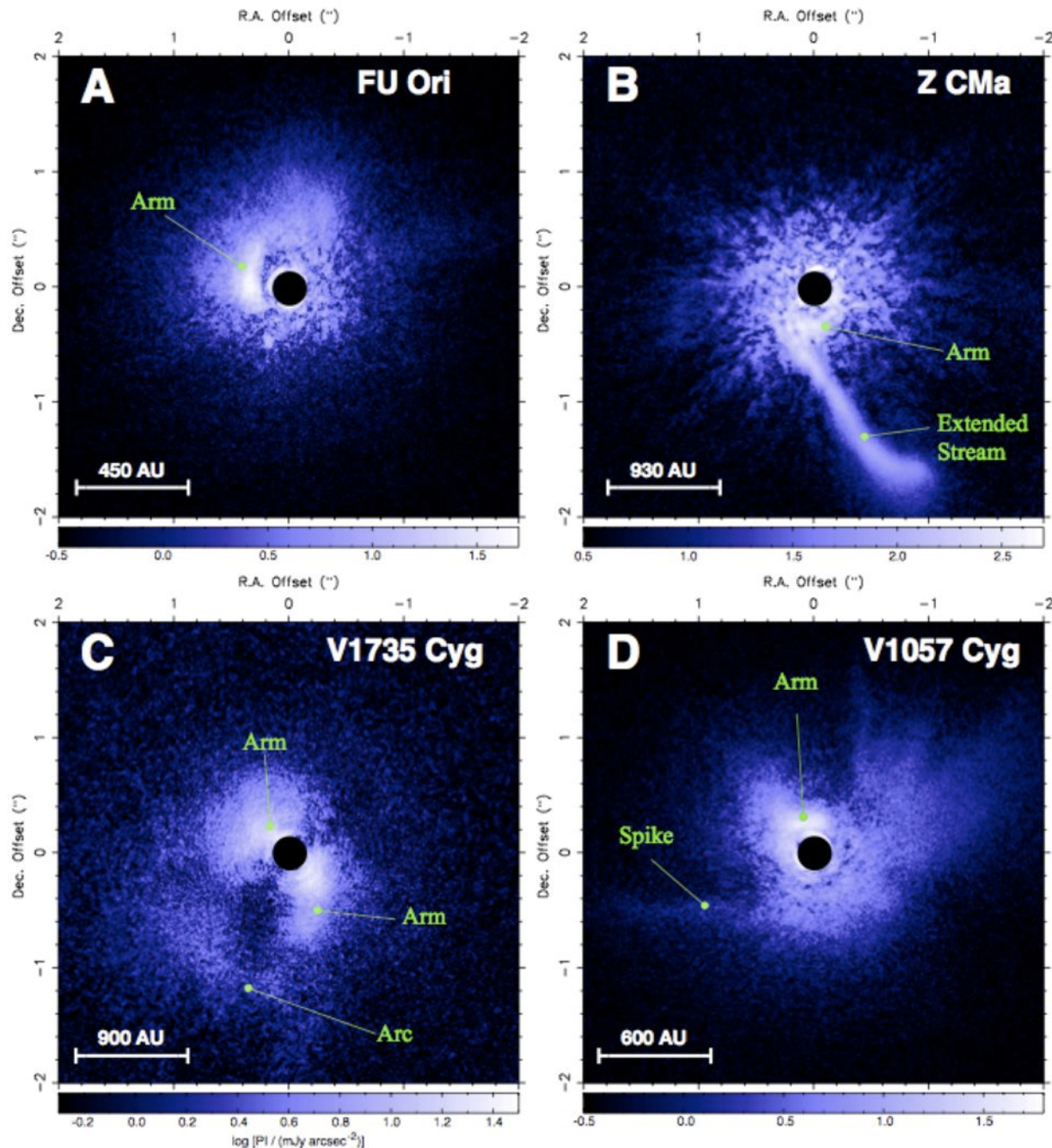


Figure 1: Circumstellar structures revealed by Subaru-HiCIAO. The scale bars are shown in AUs (astronomical units). One AU is the average distance from the sun to the earth. The gas and dust surrounding baby stars (their food) are significantly more extended than our solar system. Here we show the first observations of such complex structures around active young stars.

Estrelas Herbig Ae/Be

- A versão mais massiva de estrelas T Tauri
- Têm fortes linhas de emissão (por isso a designação Ae/Be)
- Massa $\sim 2 - 10 M_{\text{Sol}}$
- Tempo de vida curto $\rightarrow$ pouco estudadas

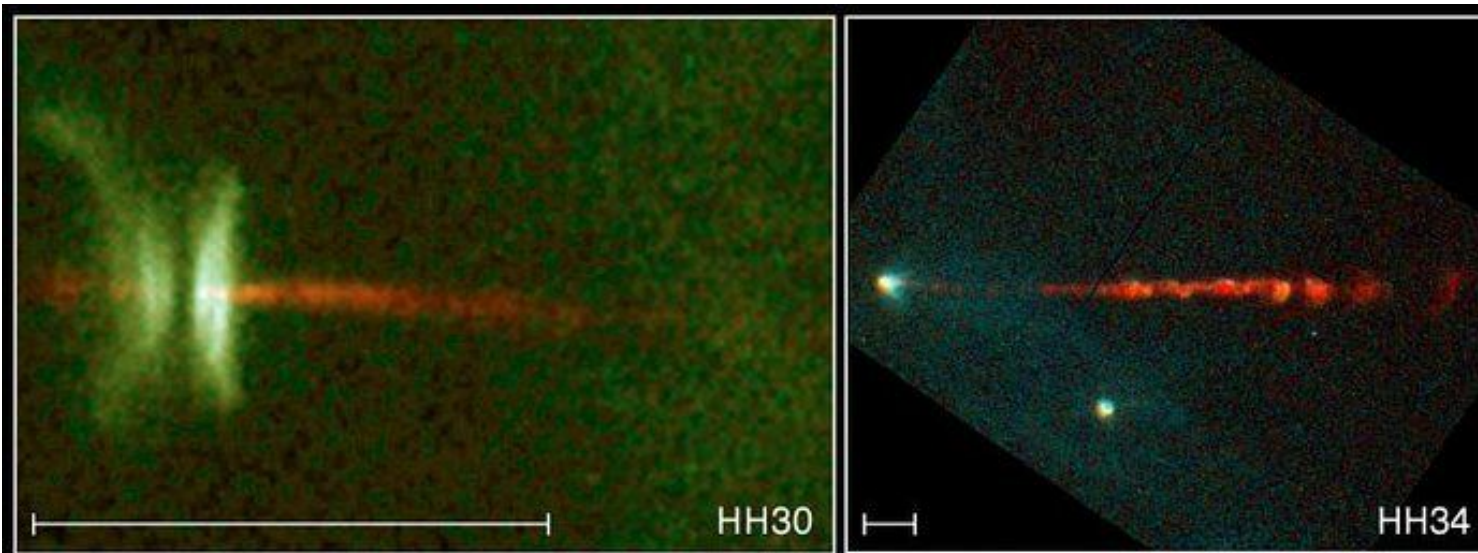
Objetos Herbig-Haro

- Relacionados a jatos produzidos por proto-estrelas como as T Tauri



Jets from Young Stars • HH1/HH2 HST • WFPC2
PRC95-24c • ST ScI OPO • June 6, 1995 • J. Hester (AZ State U.), NASA

FIGURE 12.18 (a) The Herbig–Haro objects HH 1 and HH 2 are located just south of the Orion nebula and are moving away from a young protostar hidden inside a dust cloud near the center of the image. [Courtesy of J. Hester (Arizona State University), the WF/PC 2 Investigation Definition



Upper left image: Protostellar object called HH-30 reveals an edge-on disk of dust encircling a newly forming star. Light from the forming star illuminates the top and bottom surfaces of the disk, making them visible, while the star itself is hidden behind the densest parts of the disk.



Jets from Young Stars
 PRC95-24a · ST ScI OPO · June 6, 1995
 C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

HST · WFPC2

Upper right: A more distant jet in object HH-34 shows a beaded structure, produced by a blast of 'bullets' of dense gas ejected from the star at speeds of ~805 thousand kilometres per hour.

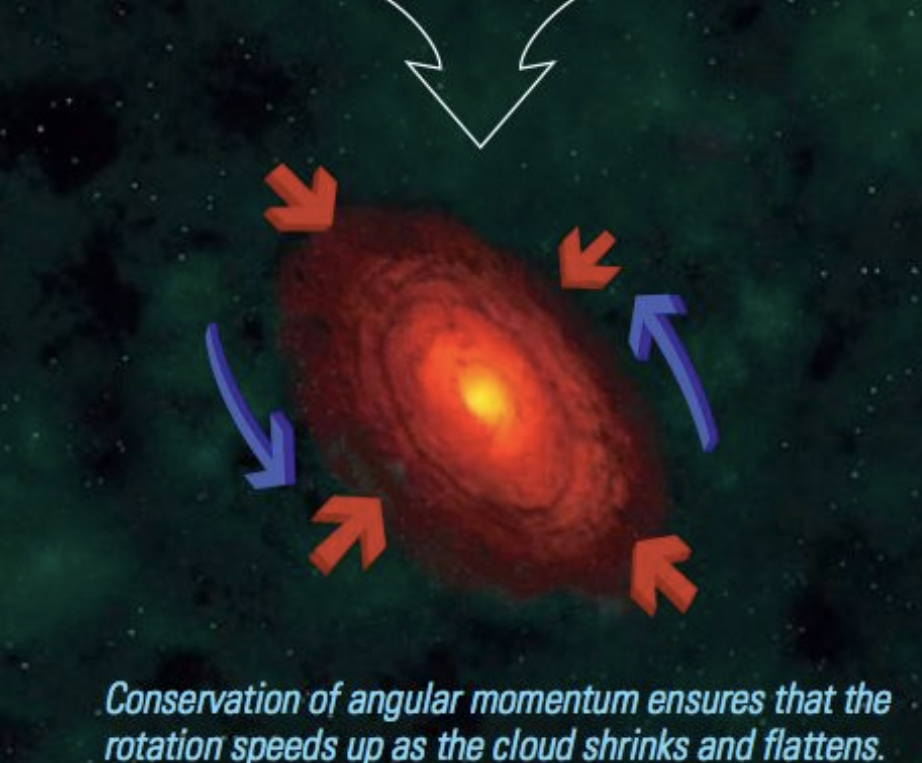
Bottom image: This view of a three trillion mile-long jet called HH-47 reveals a very complicated jet pattern that indicates the star (hidden inside a dust cloud near the left edge of the image) might be wobbling, possibly caused by the gravitational pull of a companion star.

Formação de disco e jatos em proto-estrelas



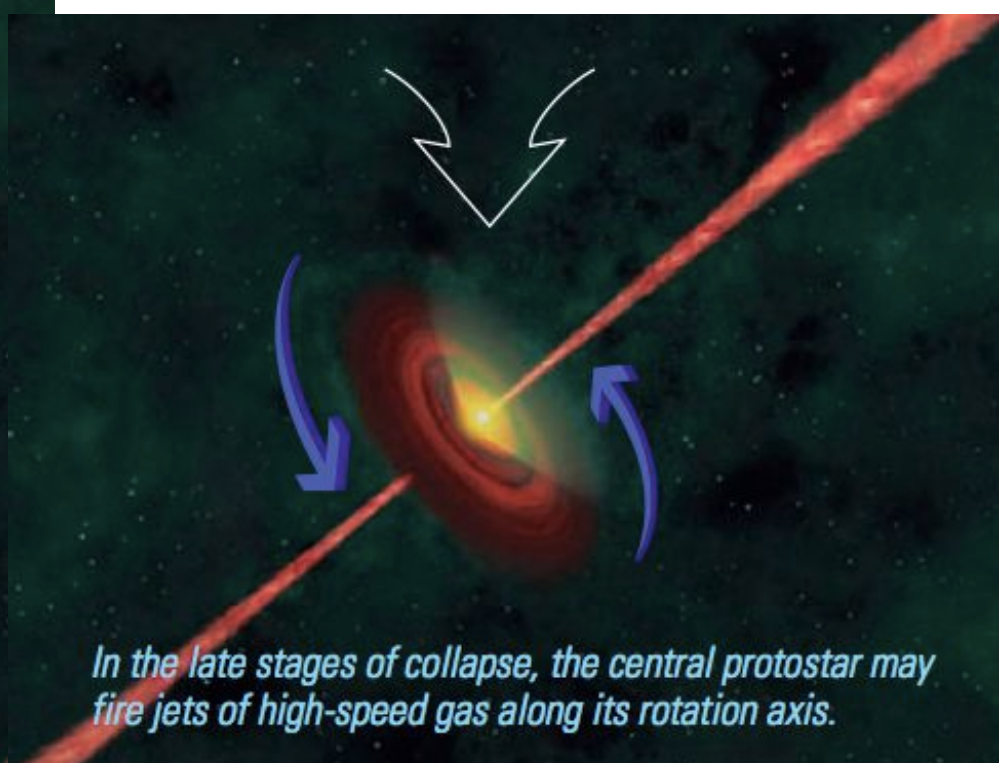
A contracting cloud fragment always has some small, overall rotation.

The diagram shows a dark, reddish-brown cloud fragment in space. Several blue arrows point towards the center, indicating contraction. Several orange arrows point in a circular path around the fragment, indicating rotation. A white V-shaped arrow points from the text above to the fragment.



Conservation of angular momentum ensures that the rotation speeds up as the cloud shrinks and flattens.

The diagram shows a protostar, a bright yellow-orange sphere, surrounded by a flattened disk of gas and dust. Blue arrows indicate the disk's rotation. Two long, narrow jets of gas extend from the poles of the protostar. Orange arrows show the original cloud fragment contracting. A white V-shaped arrow points from the text above to the protostar.



In the late stages of collapse, the central protostar may fire jets of high-speed gas along its rotation axis.

The diagram shows a protostar, a bright yellow-orange sphere, surrounded by a flattened disk of gas and dust. Blue arrows indicate the disk's rotation. Two long, narrow jets of gas extend from the poles of the protostar. Orange arrows show the original cloud fragment contracting. A white V-shaped arrow points from the text above to the protostar.

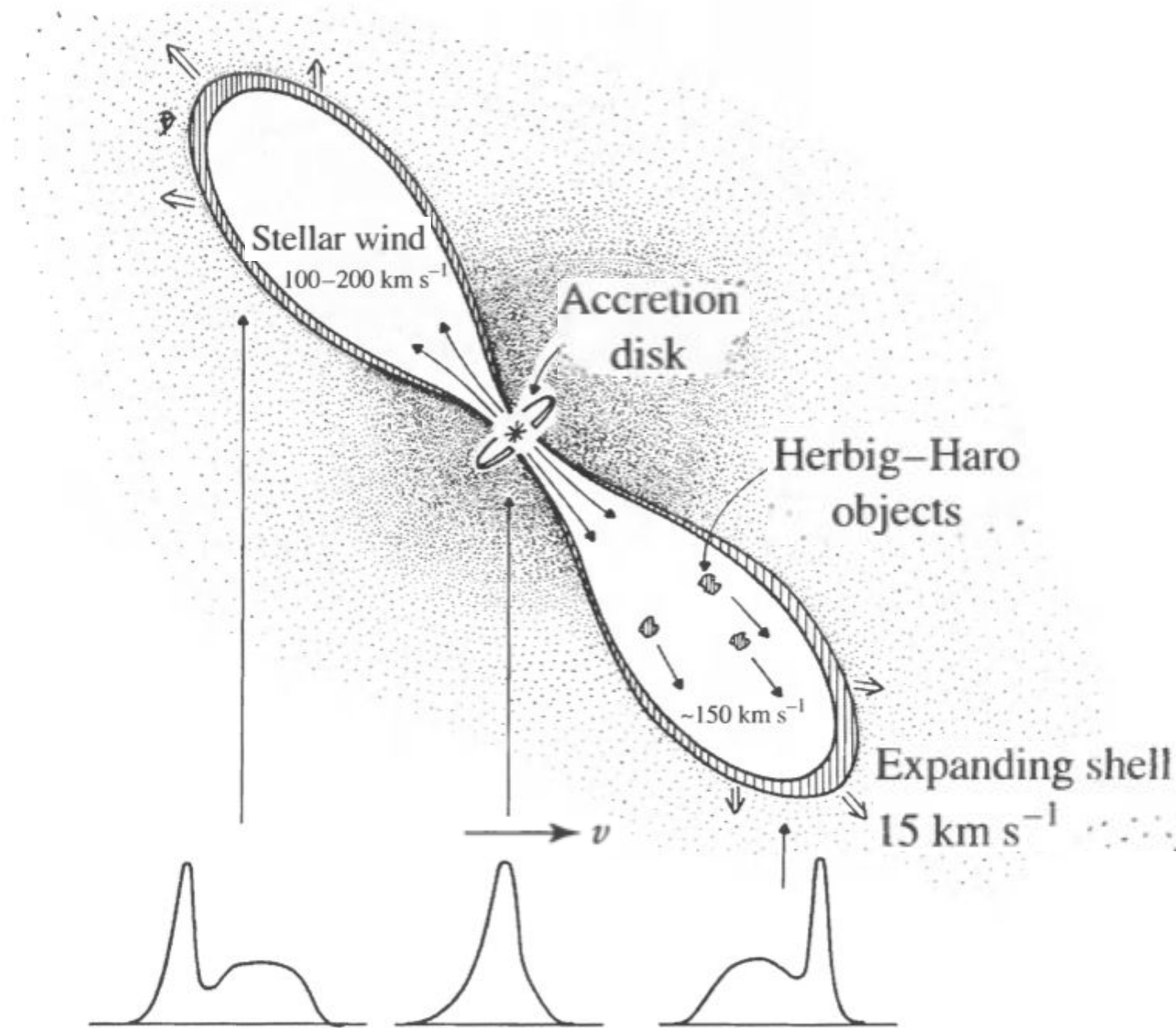


FIGURE 12.20 An early model of a T Tauri star with an accretion disk. The disk powers and collimates jets that expand into the interstellar medium, producing Herbig-Haro objects. (Figure adapted from Snell, Loren, and Plambeck, *Ap. J. Lett.*, 239, L17, 1980.)

Estrelas jovens com discos circumestelares

Disco de detritos
em estrela jovem

Material para
formar planetas?

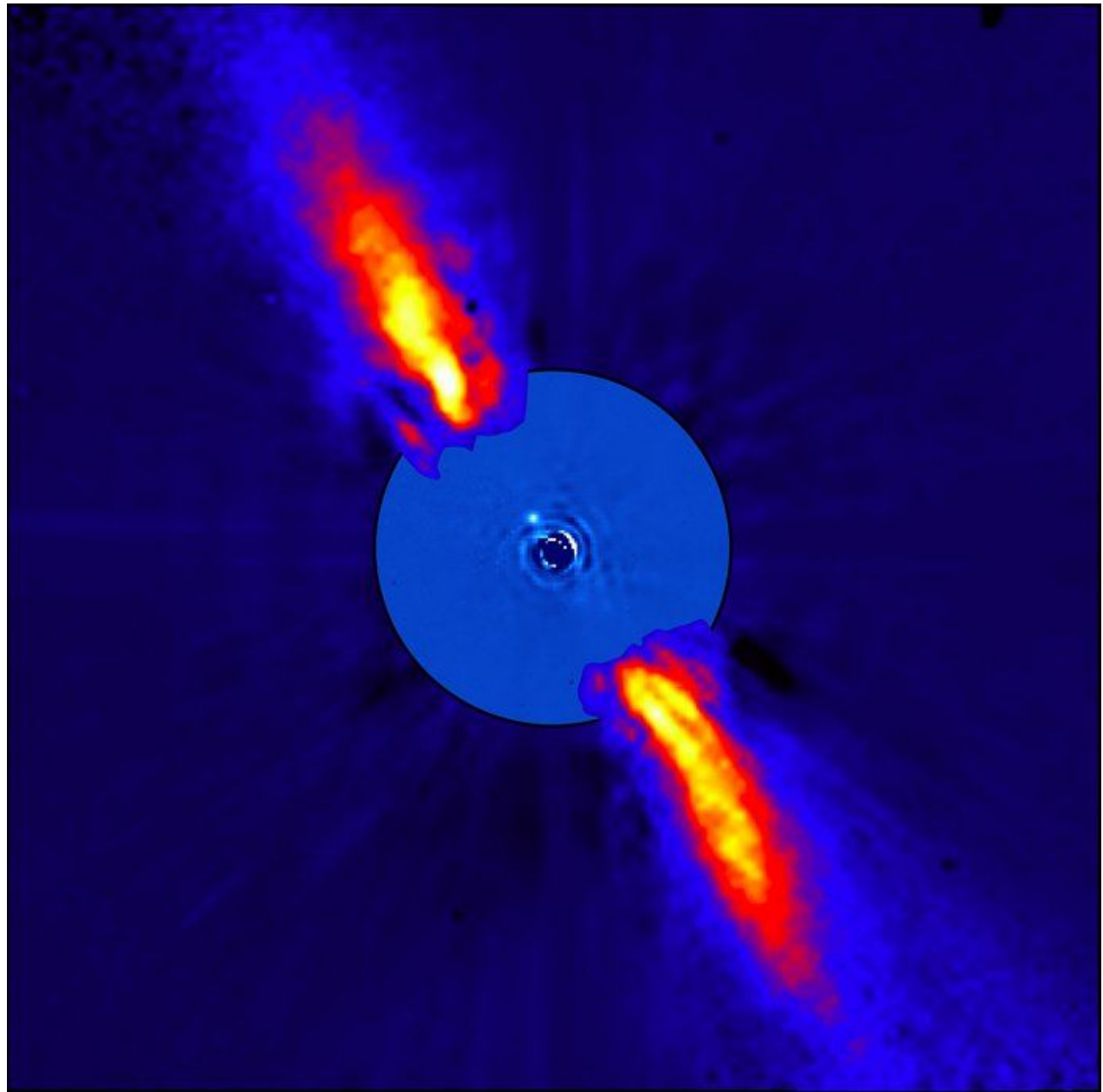
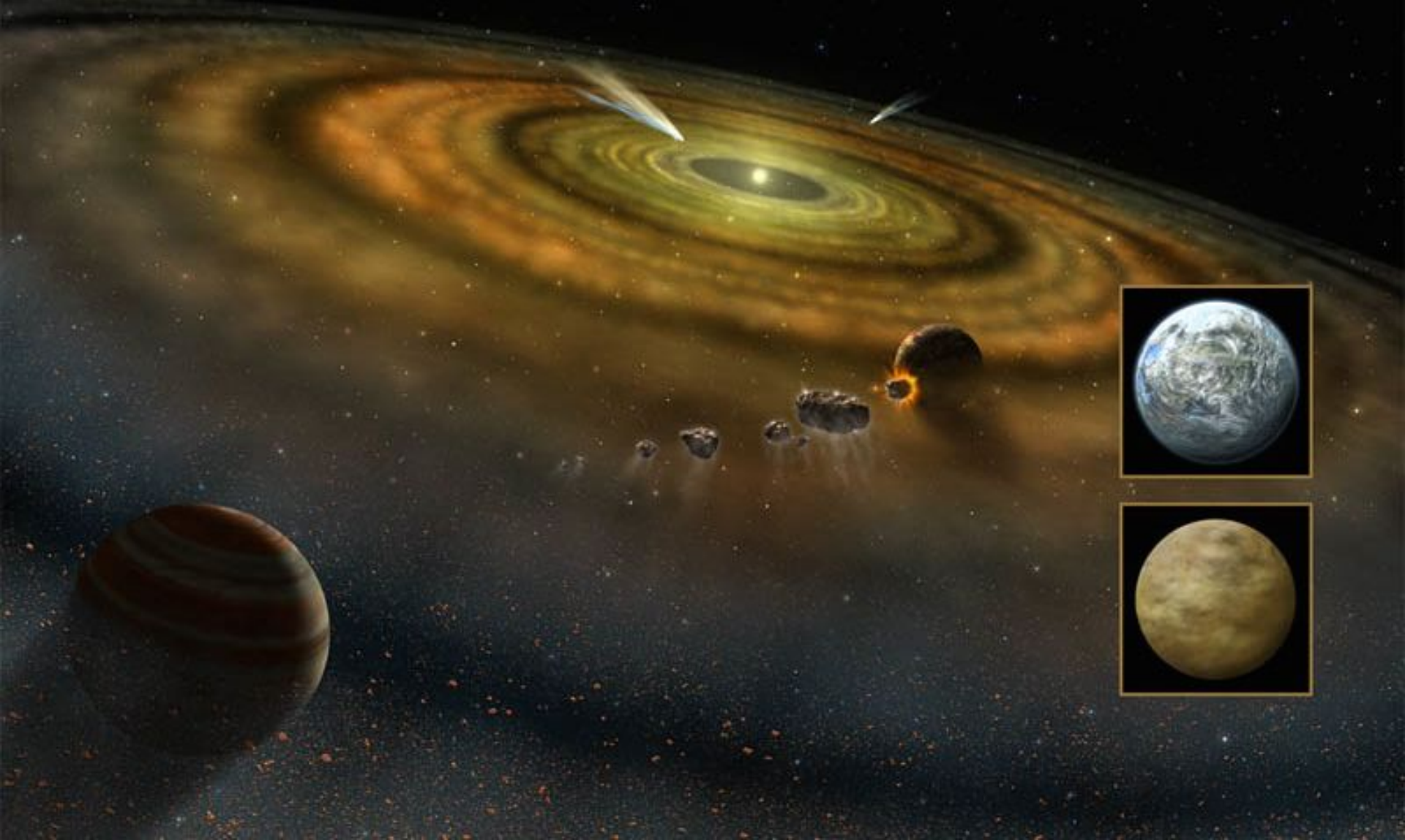


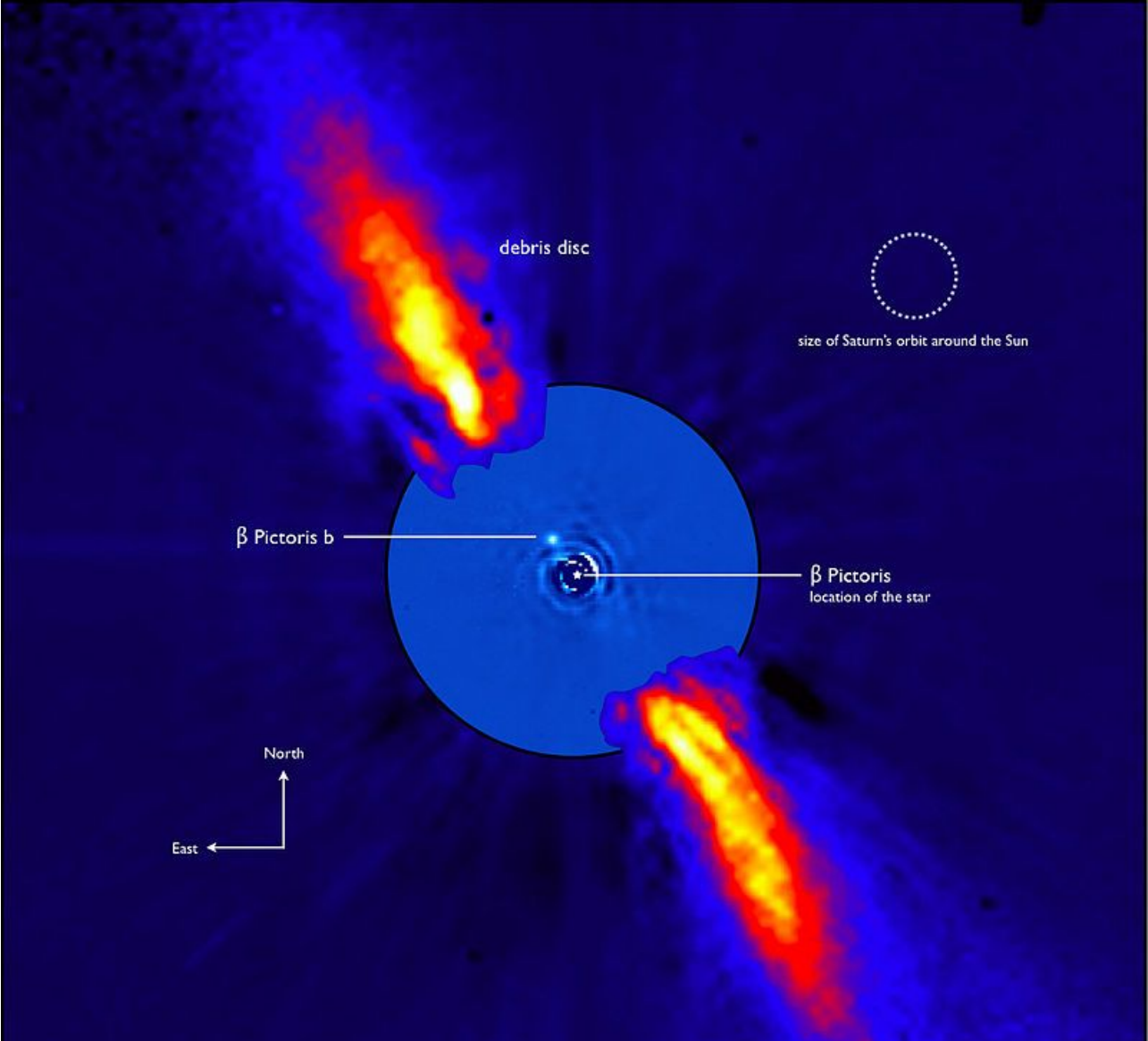
FIGURE 12.21 An infrared image of β Pictoris, showing its circumstellar debris disk. (European Southern Observatory)



Impressão artística do disco de detritos ao redor de Beta Pictoris, mostrando formação planetária, exocometas e planetesimais

<http://imagine.gsfc.nasa.gov/Images/bios/roberge/BetaPictoris.jpg>

Imagem infravermelha tirada pelo Observatório Europeu do Sul, mostrando o disco de detritos e o planeta Beta Pictoris b



Planeta (a partir da estrela)	Massa	Semieixo maior (UA)	Período orbital (d)	Excentricidade orbital	Inclinação (°)	Raio
b	$7_{-3}^{+4} M_J$	$9,2_{-1,5}^{+0,4}$	7890 ± 1000	$\sim 0,1$	$89,01 + 0,36$	$1,65 R_J$

Proplyds in Orion

Discos protoplanetários em Orion

Massa $\sim 2 \times 10^{25}$ kg ($M_{\text{Terra}} \sim 6 \times 10^{24}$ kg)



Proplyds in Orion

(c) HST

Discos protoplanetários em Orion

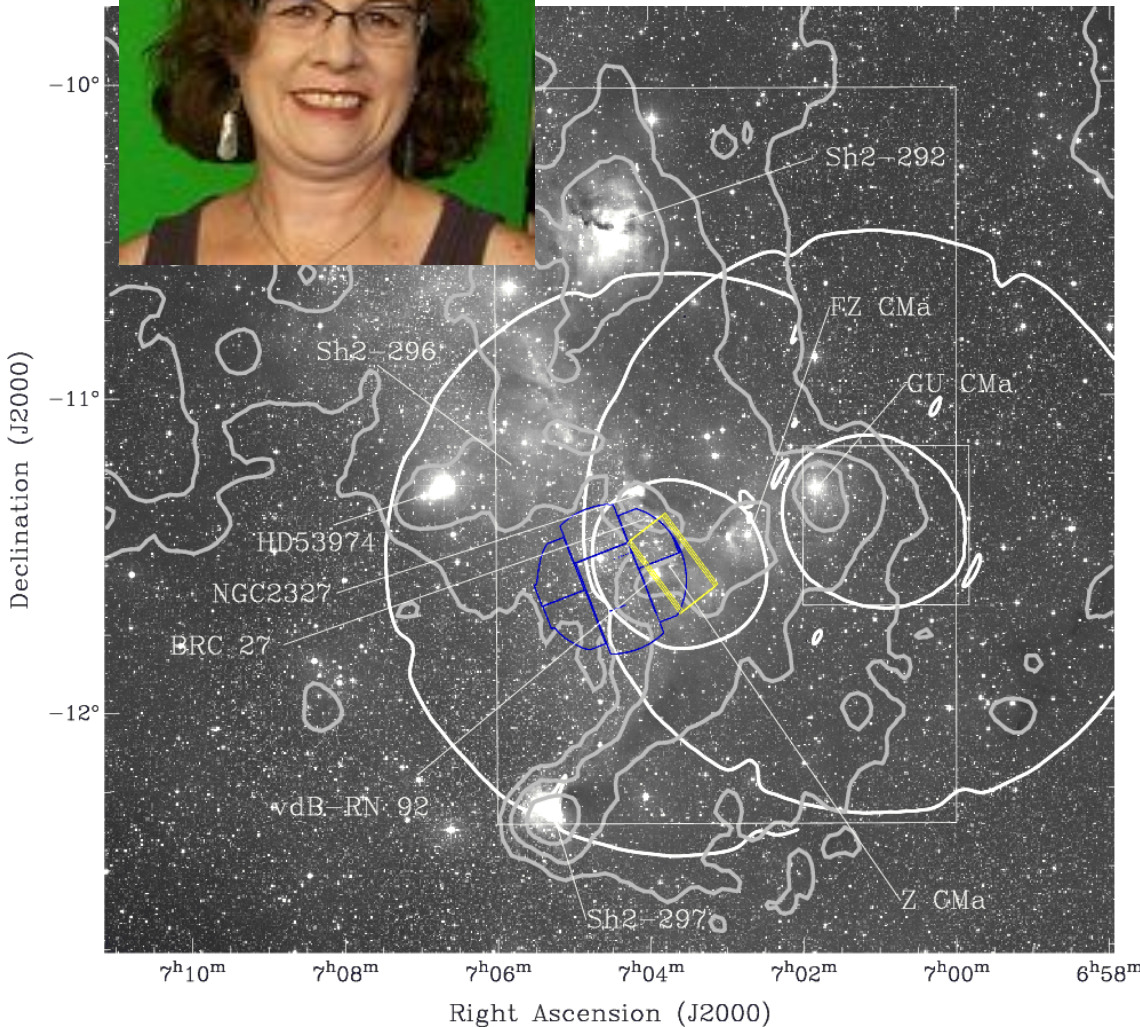


Estudo de estrelas jovens no Brasil



Profa. Jane Gregorio
Hetem (IAG/USP)

Profa. Silvia Alencar
(UFMG)



V 830 Tau, estrela T Tauri



Região de formação de estrelas CMa R1

Provinha

- 1) Qual escala de tempo é maior, “free fall” da nuvem ou “Kelvin-Helmholtz” de contração da proto-estrela?
- 2) Qual a primeira reação nuclear no estágio de proto-estrela: queima de deutério ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$ ou o começo da cadeia p-p? ${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + e^+ + \nu_e$
- 3) Em uma região de formação estelar, são formadas mais estrelas de alta ou baixa massa? [IMF]
- 4) Que tipo (espectral) de estrelas é a fonte dos fótons para ionizar as regiões HII?